HABILITATION THESIS

MODELAREA SISTEMELOR DE PRODUCȚIE PRIN UTILIZAREA INSTRUMENTELOR SPECIALIZATE DE TIP REȚELE PETRI CU APLICAȚIE ÎN MONITORIZAREA ȘI CONTROLUL SISTEMELOR DE FABRICAȚIE

THE PRODUCTION SYSTEMS MODELLING BY SPECIALIZED PETRI NETS TOOLS WITH APPLICATION IN THE MONITORING AND CONTROL OF MANUFACTURING SYSTEMS

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CONTENTS

Notations and abbreviations

FT	*Faults tree*
AFMEC	*Analysis of Failure Modes, Effects and Criticity*
WD	*« watch dogs » signals*
HMI	*Human Machine Interface*
ISO	*International Organization for Standardization*
CG	*Causality Graph*
CMMS	*Central Maintenance Managemente System (fr :Gestion de la Maintenance Assistée par l'Ordinateur)*
FPN	*Fuzzy Petri Nets*
RFPN	*Recovery Fuzzy Petri Nets*
MFPN	*Monitoring Fuzzy Petri Nets*
OOPN	*Oriented-Object Petri Nets*
TOOPN	*Temporal Oriented-Object Petri Nets*
SCADA	*Supervisory Control and Data Acquisition*
DES	*Discrete events system*
FSI	*Fuzzy system interface*
TG	*« Watch Dogs » transition*
AI	*Artificial Intelligence*
CR	*Abnormal feedback signals (fr: "les comptes rendus anormaux")*

List of Figures

Part I

Thesis Summary

Thesis Summary

This thesis cumulates the results of research undertaken towards modelling production systems, by using specialized Petri Nets tools. The results of this research were applied in monitoring and control production systems.

The modern control of production systems is becoming more and more difficult, because of the considerable number of parameters, disturbances, but also restrictions and quality requirements which are enforced by an increasingly competitive environment. Developing intelligent tools, capable of integrating production and maintenance restrictions based on intelligent decision-making techniques, represents the solution that engineering suggests for production systems. In this context, industrial maintenance takes on an increasingly greater role in the modern management of production systems, allowing for the organization and control of the systems in a more and more restrictive environment. Production systems management aims at developing the company, in the sense that it increases its profits, either through integrated production and maintenance management, or through externalizing these functions so that they may be undertaken by specialized companies.

The research described in this paper integrates artificial intelligence techniques, more precisely fuzzy logic, in order to define and implement specialized tools in modelling the monitoring and maintenance functions of processes, in an DES approach. To that effect, we suggest a homogenous approach to modeling, based on Fuzzy Petri Nets tools (*FPN*) as instruments dedicated to monitoring, maintaining and directing production systems.

For each instrument we conceived an interfacing mechanism that allowed for the implementation of the Control-Process-Monitoring-Decision loop. In the practice of industrial maintenance, this loop is used as a decisional support system and it includes two basic stages: the validation of each stage by the maintenance manager, followed by the implementation of the maintenance policies by a specialized operator. The integration of fuzzy logic into a modelling tool for the monitoring process, but also for the support system for making corrective decisions, allows for the implementation of a formalization as close as possible to the reality of the informational system.
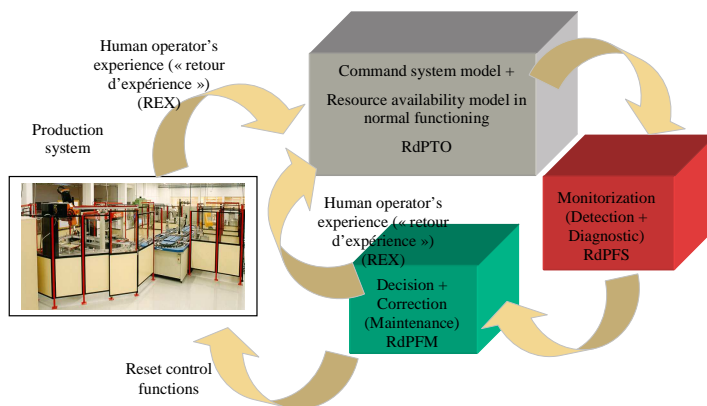
For that purpose, this paper suggests, as a first stage, the elaboration of a cooperative model that interfaces the command system model with the material resources model for a normal functioning. The two models are built with Temporal *Oriented-Object PN* (*TOOPN*) in which the token is associated with classes of features and with methods corresponding to the characteristics of the normal or degraded functioning mode. Modelling is based on the hypothesis that possible faults are known apriori and modeled through specific methods. Therefore, this model also contains a direct fault detection function. Fault detection is translated in PN models through "watch dogs"

mechanisms. These mechanisms emit signals for synchronization with the PN models that they are interfaced with.

At the level of each monitored process, the hypothesis states that we have a knowledge base regarding the causal evolution of the fault state. This knowledge is organized in causal logical descriptions, known as "faults tree" (FT) (*fr. l'arbre des défauts et de défaillance ADD*). For refining the information sent by the direct detection in the guise of defect signals, we have defined a tool specialized in the fuzzy analysis of the information acquired. This instrument was called Monitoring Fuzzy Petri Nets (*fr :* Réseau de Petri Flou pour la Surveillance (*MFPN*)). The instrument proposes the association of a fuzzy description to the variable „*the temporal window in which the defect might appear*", which allows for the evaluation of the gravity of the received fault. Moreover, in order to confer its decisional aspect, we must resort to control values, associated to certain events that are considered to be critical.

The suggested instrument is an extension of the Petri Net Object typology (fr: type réseau de Petri à Objects) (*OOPN*) and Fuzzy Petri Net typology (fr: réseau de Petri Flou (*FPN*)), known in the specialized literature and adapted to the modelling of fuzzy type reasoning. The originality of this approach lies in a specific algorithm, destined to the modelling of detection/decision functions in a fuzzy temporal approach. The proposal was adapted to the problems of monitoring the processes of the production systems type. Starting from the faults tree (*FT*) of the monitored system, we suggest an analysis/decision tool based on fuzzy rules that ensue from the propagation of faults in FT. The control values, imposed by definition, represent the materialization of the gravity limits of the faults that classify these states as being unwanted.

The control values are defined through repeated experiences/analyses/interpretations of critical contexts from the point of view of failure situations within the process. The repetition of these functioning scenarios with a potential for failures allows the fuzzy modelling of the occurrence of faults in critical temporal windows associated to them. The utilization of FT which describes the causal chain of faults, as well as the fuzzy modelling of the moments when the faults appear, give the suggested tool a *fuzzy temporal* aspect.

The dynamics of the proposed tool allows the identification of the degradation state for the monitored process, as well as of its gravity value at any moment. The predictive aspect of the model associated with fuzzy monitoring is materialized through the evolution of *MFPN* according to the faults that have occurred. On the other hand, the decisional aspect of the model is integrated into the comparison algorithm for the values that characterize the gravity of the faults and the control values settled apriori.

The proposed mechanism is based on the following techniques and arguments: the suggested monitoring model requires information about the faults that have occured, in the interface. These information are supplied by the direct detection function that delivers synchronization signals between the functioning model of the system and the fuzzy monitoring model. Due to the structural incompatibility between the two models typologies, since they use objects with different attributes and methods, the two models communicate in the interface with synchronization signals. The models evolve synchronically and allow for the identification in real time of the parallel evolutions: the model associated with the the dynamics DES evolution for the monitored system and the model which describes the evolution of the degradation state of the system.

On the other hand, the model that corresponds to the fuzzy monitoring function delivers signals that require corrective actions, according to the strategy implemented in the supervising model. The predictive aspect require correction, only if the model associated to monitoring functions indicates critical values for the control values associated with faults FT.

The faults correction mechanism will be modeled through another RP-type specialized tool, built on the same fuzzy approach concepts. The model for the recovery/correction of the degraded state was built with a dedicated instrument: the Fuzzy Petri Nets for Recovery (Maintenance) (fr: Réseau de Petri Flou pour la Maintenance) *RFPN* which models an expert fuzzy system. The suggested *RFPN* tool preserves the fuzzy temporal aspect through the real-time exchange of information with the fuzzy monitoring model.

This tool functions in double interface with monitoring systems and real-time process through synchronization signals. In the development of this new instrument, the entities used as input variables – a "Symptom" of the possible faults and the rule bases that describe the dependence between causes (occured faults) and the effects of their occurence. The transitions of the *RFPN* model materialize the generalized modus ponens operator, which sits at the base of the composition between inputs and the logical rules basis. Model outputs are also fuzzy temporal signals.

The global model for fuzzy supervising has the consistency of a hybrid model, because of the different typology of the signals that are found in the interface of models (synchronization signals that are associated to different fuzzy values in definition structures oriented towards objects) as well as the different typology of models (*MFPN*, *RFPN*, *TOOPN*). The model interface informations are transferred through emission/reception signals. This mechanism is based on the Petri Nets model with internal synchronizations.

The first chapter is dedicated to the analysis of industrial maintenance and monitoring techniques, in the context of modern production, as well as the following concepts: tele-maintenance, e-maintenance, maintenance and intelligent monitoring. In **Chapter 2** we present the state of the arts of research in the industrial monitoring domain, insisting upon the modelling with Petri Nets. The chapter introduce monitoring systems typologies specific to monitoring techniques based on a model or not. We particularize the components of the monitoring system, as well as the modelling techniques for specific functions: detection/diagnostic.

Chapter 3 is dedicated to Fuzzy Petri Nets as a tool specialized in intelligent monitoring. The suggested instrument is an adaptation of Fuzzy Petri Nets destined to the modelling of logical arguments, of modelling the logical rules basis that ensues from the causal description of the occurrence and development of critical states. This approach is presented in the subchapter dedicated to dynamic monitoring. The conceptual presentation of *MFPN*, as well as of the theoretical aspects of dynamic monitoring, are improved through the implementation of an e-maintenance platform destined for the control of a production system, as seen in **Chapter 4**. The chapter presents extensions of *MFPN* through defining another instrument dedicated to the corrective maintenance action. The Petri Nets for Maintenance tool (*RFPN*) models a fuzzy expert system.

Chapter 5 presents a solution to the refinement of the monitoring function. We propose an instrument of the type *MFPN*, integrated into a hierarchical structure, interfaced with the *PN* model of direct detection: *RecSinFPN – Recurrent and Synchronized Fuzzy Petri Nets*. Beside the presentation of the concepts that the definition of *RecSinFPN* is based on, the tool is used by applications destined for the elaboration of monitoring functions models specific for production systems, as well as production systems served by cooperative robots (**Chapter 6**).

The theme of modelling production systems serviced by cooperative robots is continued in **Chapter 7**, destined for the *generalized* modelling *of manufacturing systems destined for repetitive actions*, with particularization on actions of assembly/disassembly. The model associated to these systems is created with specialized instruments of the *SHPN* type. The generalized model, as well as the analysis for optimization of the cycle time, are particularized on a laboratory production system, for which the real-time directing platform was created. The

SHPN model associated with the directing of the mechatronic system destined for assembly/disassembly, serviced by collaborative robots, highlights the real-time directing strategy of the process, implemented under the LabView platform.

Rezumatul tezei

Această teză cumulează rezultatele cercetarilor efectuate în direcția modelării sistemelor de producție prin utilizarea instrumentelor specializate de tip Rețele Petri. Rezultatele acestor cercetari au fost aplicate în monitorizarea și controlul sistemelor de fabricație.

Conducerea sistemelor de producție moderne devine din ce în ce mai dificila datoriră numărului considerabil de parametrii, perturbații dar și restricții și cerinte de calitate impuse de un mediu din ce în ce mai concurențial. Dezvoltarea instrumentelor inteligente capabile să integreze restricții de producție și mentenața bazate pe tehnici inteligente de luare a deciziilor, reprezintă soluția pe care o propune ingineria sistemelor de producție. In acest context, mentenața industrială ocupa un loc din ce în ce mai important în managementul modern al sistemelor de producție, permițând organizarea și conducerea sistemelor într-un mediu din ce în ce mai restrictiv. Managementul sistemelor de producție țintește spre dezvoltarea întreprinderii în sensul creșterii profitului fie prin managementul integrat de producție și mentenața, fie prin externalizarea acestor funcții spre a fi preluate companii de specialitate.

Cercetările propuse în această lucrare integreaza tehnici de inteligență artificială, mai precis logica fuzzy, pentru definirea și implementarea instrumentelor specializate în modelarea funcțiilor de monitorizare și mentenața a proceselor, în abordare SED. In acest sens, se propune o abordare omogenă în modelare, bazată pe instrumente de tip Rețele Petri Fuzzy (MFPN) ca instrumente dedicate monitorizarii, mentenației și conducerii sistemelor de producție.

Pentru fiecare instrument s-a conceput un mecanism de interfațare care face posibilă implementarea buclei *Control-proces_Monitorizare_Decizie*. In practica mentenației industriale, acesta buclă este utilizata ca sistem suport decizional, ea incluzând doua etape de bază: validarea fiecărei etape de către managerul de întreținere, urmată de aplicarea politicilor de mentenață de către un operator specializat. Integrarea logicii fuzzy într-un instrument de modelare a procesului de monitorizare dar și a sistemului suport de luare a deciziilor corective, permite implementarea unui formalizări cat mai aproape de realitatea sistemului informațional.
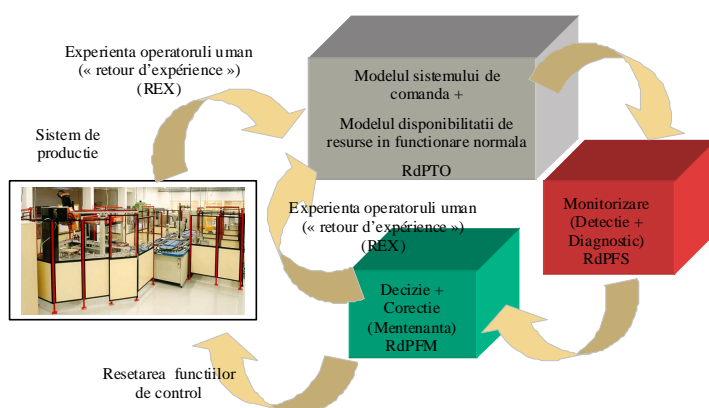
In acest sens, în lucrare se propune intr-o prima etapa elaborarea unui model colaborativ care interfatează modelul sistemului de comandă cu cel al disponibilitatii resurselor fizice pentru o funcționare normală. Cele doua modele sunt construite cu *PN* temporale orientate pe obiecte (*TOOPN*) în care jetonul

are asociate clase de proprietați și metode corespunzatoare caracteristicilor modului de funcționare normal sau degradat. Modelarea are la baza ipoteza ca defectele posibile sunt apriori cunoscute și modelate prin mecanisme specifice. Astfel acest model conține și funcția de detecție directa a defectelor. Detecția defectelor este tradusa în modelele *PN* prin mecanismele „watch dogs". Aceste mecanisme emit semnale de sincronizare cu modelele *PN* cu care aceste semnale sunt interfațate.

La nivelul fiecarui proces monitorizat, prin ipoteza se dispune de o bază de cunostințe privind evolutia cauzală a starii de defect. Aceste cunostinte sunt organizare în descrieri logice cauzale, cunoscute sub denumirea de *Arbore de defecte şi stari critice* (*fr:* l'arbre des défauts et de défaillance ADD, *en:* faults tree FT). Pentru rafinarea informatiei trimise de detecția directă sub forma semnalelor de defect, s-a definit un instrument specializat în analiza fuzzy a informațiilor achizitionate. Acest instrument a fost denumit **Reţele Petri pentru Monitorizare** (*fr :* Réseau de Petri Flou pour la Surveillance (*MFPN*)). Instrumentul propune asocierea unei descrieri fuzzy variabilei *fereastra temporala în care este posibila aparitia defectului*, ceea ce permite evaluarea „gravitații" defectului receptionat. In plus, pentru a i se conferi aspectul decizional, se apelează la valori de prag asociate anumitor evenimente considerate critice.

Instrumentul propus este o extensie a tipologiilor Reţele Petri Obiect (*fr:* type réseau de Petri à Objets (*OPN*)) şi Reţele Petri Fuzzy (*fr:* réseau de Petri Flou (*FPN*)), cunoscute în literatura de specialitate şi adaptate modelarii raţionamentelor de tip fuzzy. Originalitatea abordării propusă în cadrul acestor cercetări constă într-un algoritm specific destinat modelarii funcţiilor detectie/decizie într-o abordare fuzzy temporală. Propunerea a fost adaptată la problematica monitorizării proceselor de tip sisteme de fabricaţie. Pornind de la arborele de defecte FT al sistemului monitorizat, se propune un instrument de analiza/decizie bazat pe reguli fuzzy care decurg din propagarea defectelor în FT. Valorile de prag, impuse prin definiţie, reprezintă materializarea limitelor de gravitate a defectelor care clasifica aceste stari ca fiind nedorite.

Valorile de prag sunt stabilite prin experiente/analize/interpretari repetate ale contextelor critice din punctul de vedere al situatiilor de pana ale procesului. Repetarea acestor scenarii de funcţionare cu potenţial de defectare, permite modelarea fuzzy a apariţiei defectelor în ferestre temporale critice asociate acestora. Utilizarea FT care descrie înlantuirea cauzală a defectelor, ca şi modelarea fuzzy a momentelor de apariţie a defectelor, conferă instrumentului propus un aspect *fuzzy temporal.*

Dinamica instrumentului propus permite identificarea în fiecare moment, a starii de degradare a procesului monitorizat precum şi a valorii de gravitate a acesteia. Aspectul predictiv al modelului asociat monitorizarii fuzzy, este materializat prin evolutia *MFPN* în funcţie de defectele produse. Pe de alta parte, aspectul decizional al modelului este integrat în algoritmul de comparaţie între valorile care caracterizeaza gravitatea defectelor şi valorile de prag stabilite apriori.

Mecanismul propus este are la baza urmatoarele tehnici şi rationamente: modelul de monitorizare propus solicită în interfaţă informaţii despre defectele produse. Aceste informaţii sunt furnizate de functia de detectie directa care livreaza semnale de sincronizare între modelul de functionare a sistemului şi cel de monitorizare fuzzy. Datorita incompatibilitatii de structurale între cele doua tipologii de modele, acestea utilizand obiecte cu atribute şi metode diferite, cele doua modele comunica în interfaţă cu semnale de sincronizare. Modelele evolueaza de maniera sincrona şi pemit identificarea în timp real a evolutiilor paralele: modelul asociat dinamicii DES a sistemului monitorizat şi cel care descrie evolutia starii degradare a sistemului.

Pe de alta parte, modelul corespunzator funcţiei de monitorizare fuzzy, furnizeaza semnale care solicită acţiunii de corecţie în funcţie de strategia implementată în modelul de supervizare. Aspectul predictiv reclamă corecţia, doar dacă modelul asociat funcţiilor de monitorizare indică valori critice pentru valorilor de prag asociate defectelor din FT.

Mecanismul de corecţie a defectelor va fi modelat printr-un alt instrument specializat de tip RP, construit pe baza acelorasi principii de abordare fuzzy. Modelul de recuperare/corecţie a stării degradate a fost construit cu un instrument dedicat : **Reţele Petri Fuzzy pentru Mentenaţa** (*en. :* Recoveri, *fr :* reprize) – *fr :* Réseau de Petri Flou pour la Maintenance (*RFPN*) care

modelează un sistem expert fuzzy. Instrumentul de tip *RFPN* propus, conservă aspectul temporal fuzzy prin schimbul de informaţii în timp real cu modelul de monitorizare fuzzy. Acesta funcţionează în dubla interfaţă cu sistemele de monitorizare şi proces timp-real prin intermediul semnalelor de sincronizare. In dezvoltarea acestui nou instrument, s-au utilizat ca entitati, variabilele de intrare – « *Simptom* » ale defectelor posibile şi bazele de regului care descriu dependenta între cauze(defecte produse) şi efectele producerii acestora. Tranziţiile modelului *RFPN* materializează operarorul modus ponens generalizat, care se afla la baza compoziţiei dintre intrari şi baza de regului logice. Iesirile din model sunt tot semnale temporale fuzzy.

Modelul global de supervizare fuzzy, are consistenţa unui sistem hibrid prin tipologia diferită a semnalelor aflate în interfaţa modelelor (semnale de sincronizare avand asociate valori fuzzy în structuri de definitie orientate-obiect diferite) precum şi prin tipologia diferită a modelelor (*MFPN*, *RFPN*, *TOOPN*). Informaţiile din interfaţă modelelor sunt transferate prin intermediul semnalelor de emisie/recepţie, mecanismul avand la baza modelul Reţele Petri cu sincronizari interne.

Primul capitol este dedicat analizei tehnicilor de mentenaţă şi monitorizarea industrială în contextul producţiei moderne precum şi conceptele: tele-mentenanaţa, e-mentenaţă, mentenaţă şi monitorizare inteligenta. In **Capitolul 2** se prezintă starea actuala a cercetarilor în domeniul monitorizarii industriale cu accent pe modelarea cu Reţele Petri. Capitolul pune în discuţie tipologii de sisteme de monitorizare, specifice tehnicilor de monitorizare cu şi fară model. Se particularizează componentele sistemului de monitorizare precum şi tehnicile de modelare a functiilor specifice: detectie/ diagnostic.

Capitolul 3 este dedicat Retelelor Petri Fuzzy ca instrument specializat în monitorizarea inteligenta. Instrumentul propus este o adaptare a Retelelor Petri Fuzzy destinate modelarii rationamentelor logice, la modelarea bazei de reguli logice care decurge din descrierea cauzala a a aparitiei şi dezvoltarii starilor critice. Aceasta abordare este prezentată în subcapitolul destinat monitorizarii dinamice. Prezentarea conceptuala a *MFPN* precum şi a aspectelor teoretice ale monitorizarii dinamice sunt puse în valoare prin implementaea unei platforme de e-mentenaţa destinată controlului unui sistem de fabricaţie, asa cum rezultă din **Capitolul 4**. Capitolul prezintă extensii ale *MFPN* prin definiţia unui alt instrument dedicat acţiunii de mentenaţa corectivă. Instrumentul Reţele Petri pentru Mentenanţa (*RFPN*) modelează un sistem expert fuzzy.

Capitolul 5 aduce o soluţie pentru rafinarea funcţiei de monitorizare. Se propune un instrument de tip *MFPN* integrat într-o structură ierarhica, interfaţată cu modelul *PN* al detecţiei directe : *RecSinFPN-Reţele Petri Fuzzy Recurente şi Sincronizate*. Dincolo de prezentarea conceptelor care stau la baza definitiei *RecSinFPN* , instrumentul este pus în valoare prin aplicaţii destinate elaborarii modelelor funcţiilor de monitorizare specifice sistemelor de fabricaţie precum şi a sistemelor de fabricaţie deservite de roboţi colaborativi(**Capitolul 6**).

Tematica modelarii sistemelor de fabricaţie deservite de roboti colaborativi este extinsă în **Capitolul 7** destinat *modelarii generalizate a sistemelor de fabricatie destinate actiunilor repetitive*, cu particularizare pe acţiuni de asamblare/dezasamblare. Modelul asociat acestor sisteme este realizat prin instrumente specializate de tip *SHPN*. Modelul generalizat precum şi o analiza de optimizare a timpului de ciclu, sunt particularizate pe un sistem de fabricaţie de laborator, pentru care s-a realizat platforma de conducere în timp real. Modelul SHPN asociat conducerii sistemului mecatronic destinat asamblarii/dezasamblarii, deservit de roboţi colaborativi, sta la baza strategiei de conducere în timp-real a procesului, implementata sub platforma LabView.

Part II

Scientific and Professional Achievements

Chapter 1

Industrial maintenance and monitoring in the modern production context

In production systems maintenance activities, monitoring is an essential informaţional concept that analyses the state of the system, with the purpose of implementing and monitoring specific performance indicators. Monitoring functions must be able to detect, classify and diagnose faults by identifying primary causes [LEF, 00]. We may identify two essential functions specific to any monitoring system: detection and diagnostic. These functions highlight the passive character of the monitoring system, with regards to the correction or recovery of the normal functioning state (known in the technical literature as states management) ([Rac, 06]).

The combined detection, diagnostic and maintenance actions define a supervisor. In most approaches, real-time supervision is a model that evolves in parallel with the real physical system [Com, 91]. The supervisor is a dual decisional and operational mechanism. On the one hand, it sets the decisional strategy for identifying and reducing/eliminating the consequences of faults occurrence or of degradation states. On the other hand, through maintenance actions, it begins to apply corrective actions, so that the system will be restored to its normal functioning state or an acceptable degraded state.

Numerous authors have approached the domains: monitoring and industrial monitoring [Com, 91], [Com, 00], [Cus, 96], [Dev, 91], [EVS, 98], [Lef, 00] [Pou, 96], [Tog, 92], [Val, 87], [Weber, 99], [Zha, 99], [Val, 89], [Val, 94]. These papers offer an overview of the methodologies applied in the study and development of monitoring/supervision systems. To this effect, we present two distinct approaches and results [Das, 00]. The first case corresponds to the situation in which it is possible to model the system and apply classic control and automatic control concepts. It is the situation of the classical approach to systems whose dynamics is reported to a synchronous clock which measures the uniform lapse of time (continuous, or discreet – sampled over a certain period) [Pas, 02]. In case a formal model of the system cannot be elaborated, we must use artificial intelligence instruments that offer specific analysis and control methods [Dub, 90], [Dub, 01]. In this case, the monitoring and control functions are based on arguments that are logically obtained, through synthesis experiments (real, anticipated or potential) provided and validated by an expert. Artificial intelligence offers instruments which allow the development of an adaptive supervisor, through the following functions: perception, memory, learning, logic and adaptation to the new contexts ([Rac, 06]).

Among the artificial intelligence instruments, the expert systems are subordinated to a rule basis that corresponds to the ensemble of all states combinations, combinations that are selected from a combinatory explosion of possible states of the analyzed system. Since the expert systems

allow the exploitation of an important informational basis, they are usually projected to solve the complex classification or decisional support problems. Their main disadvantage ensues from its relatively rigid behavior, in a context that usually proves to be variable and evolutional.

A remarkable tool, which includes artificial intelligence techniques, is the neuronal nets modelling that describe mechanisms based on the learning notion. This tool manages to implement monitoring functions through techniques that are subordinated to human expert reasoning, applied in the specific context of these new techniques ([Rac, 06]). These instruments enjoy a high usage in dynamic monitoring applications, due to the emergence of dynamic neuronal nets, such as RBF (recurrent neuronal nets with Radial basic functions) [Zem-a,-b, 02], [Zem, 03]. The limits of the neuronal monitoring system are the lack of traceability in the reasoning or the lack of the logical route proposed as a solution.

In the end, from the point of view of the intelligent instruments destined for monitoring and control, it is the fuzzy expert systems that stand out. The particularity of such a system is that it can control numerical data and linguistic knowledge simultaneously. Fuzzy expert systems represent a collection of membership functions and reasoning rules. Unlike traditional expert systems, which are symbolic reasoning machines, fuzzy expert systems are oriented towards numeric processing. The elaboration of a fuzzy expert system is based on the fact that the human expert must have the ability to obtain efficient reasoning by exploiting imprecise, incomplete and uncertain information ([Rac, 06]).

Fuzzy expert systems, which use an uncertain knowledge basis, propose the modelling of monitoring and control strategies through combinations of rules specific for fuzzy logic. Using fuzzy logic in monitoring allows the refinement of information aquired from the field. This can be done by introducing the notion "degree of truth" (a real number between 0 and 1) associated to each statement that has a sentence/phrase value with an approximate logical value, as well as a set of approximate reasoning rules (often times progressive) capable of describing the dynamics of the monitored system and its progressive context. This technique seems promising due to its potential for usage in dynamic monitoring and prognosis, since it has the capacity to ensure a good interface with the human operator, because it imitates his manner of thinking and because it offers information about the traceability of the monitored system's states, an aspect which is essential in industrial monitoring.

For all these reasons, we have chosen to develop a fuzzy supervisor adapted to discreet events systems. The contribution of research undertaken for this purpose consists of developing two *PN* fuzzy-type specialized instruments, dedicated to the monitoring and maintenance of systems approached as discreet events systems.

In order to introduce the concepts necessary for the study ([Rac, 06]), the present paper proposes two explicative subchapters. In the first part, we will present a few definitions, elements of fuzzy logic in relation to the proposed approach. The second part of the paper is dedicated to the usage of Petri Nets for the supervision of discrete event systems (DES).

Maintenance

> *A set of technical, administrative and management activities throughout the life cycle of a product / process, which acts in the purpose of maintaining it or restoring it to a state that allows it to fulfill the required functions,*

For a long time, it was "the poor child" of industrial strategy. Apart from a few sectors – such as aeronautics, refineries, nuclear and space domains [Dek, 98], the consumer goods industry [Rac, 96] only recently found itself looking at this function as a new source of profit and optimization of the existing production means, in a demanding economical context, in which European

companies are forced to exploit all technological and organizational niche solutions, so that they may remain competitive.

Tele-maintenance

> *Diagnosing and implementing specific maintenance procedures for local stations, from the dispatcher point, without having to travel on site, is tele-maintenance*

In the industrial environment, restrictions regarding cost, technological execution, accessibility and control of industrial sites extended over significantly great geographical areas, carry the possibility of data access, distribution and sharing, as well as the optimization of long-distance maintenance actions, called *tele-maintenance*.

Tele-maintenance is being used more and more for all machines or production lines controlled by a microprocessor (Figure 1). Its implementation allows the exploitation of all process monitoring information delivered by sensors, but also their interrogation from a distance. The tele-maintenance structure is based on a hierarchical structure, so that the central control point may intervene in modifying adjustment parameters or in the structure of the programs that control the process ([Rac, 06]).
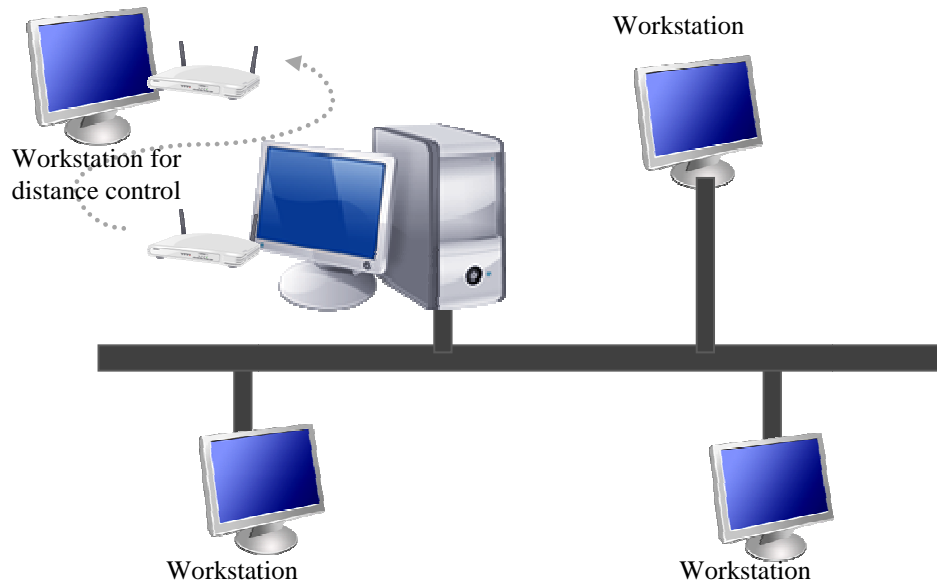
Figure 1. *Tele-maintenance flow chart*

Since the emergence of the New Technologies of Information and Communication (NTIC), Tele-maintenance concepts have evolved, turning into *e-Maintenance* (Figure 2) ([Rac, 06]):

- Tele-maintenance is a long-distance data access/recovery concept or a long-distance control concept

- E-Maintenance is a concept that connects maintenance actions to the principles of *web-services*, and *cooperation* and *knowledge sharing*
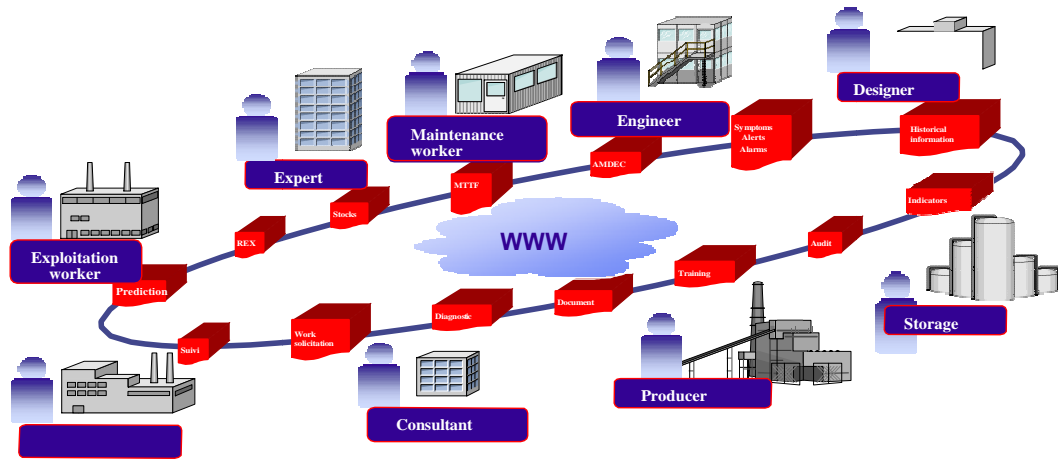
Figure 2. *E-maintenance*

E-Maintenance [Leg, 04] includes the fundamental principles of Tele-maintenance, to which it associates a stronger dimension: cooperation at an informational level, of primary industrial maintenance actions (engineering, exploitation, maintenance, operation safety, acquisitions, compatibility, etc) as well as at the level of inter-party connections (client / supplier, inter-suppliers, inter- clients, etc)

For this reason, the components of the monitoring system are characterized by an increasingly greater autonomy, by working in distributed systems and integrating embedded intelligence in most cases. If we strike a balance of the evolution of maintenance politics over time (Figure 3), we may select the following moments for information purposes ([Rac, 06]):

> ✦ The '60s : Reactive/corrective maintenance

Intervenes after the detection and localization of a fault. Reactive maintenance completely or partially (palliative) repair the observed fault, performing an intervention after the localization of the fault.

> ✦ The '70s : Preventive (preventive systematic) maintenance

Performed with the intention of reducing the failure probability of a product or for reducing the degradation of a service. This is a maintenance intervention planned, prepared and scheduled before the date estimated as the probable date of the fault occurrence. At present, preventive maintenance is applied as systematic maintenance. This represents the preventive maintenance action performed in conformity with a time planning program or according to the number of usage actions associated to a process or entity, for which functioning in normal parameters is guaranteed.

> ✦ The '80s : Predictive maintenance (previsional, preventive, conditional)

Based on the continuous monitoring of the system's evolution in order to prevent a breakdown before it takes place. It does not involve knowing the degrading law apriori. The preventive intervention decision is taken when there is experimental evidence of an imminent fault or when the system is approaching a predetermined threshold degradation. In industrial practice, this intervention is based on measuring certain process parameters: temperature, vibrations, oil quality, ..., which can anticipate a failure.
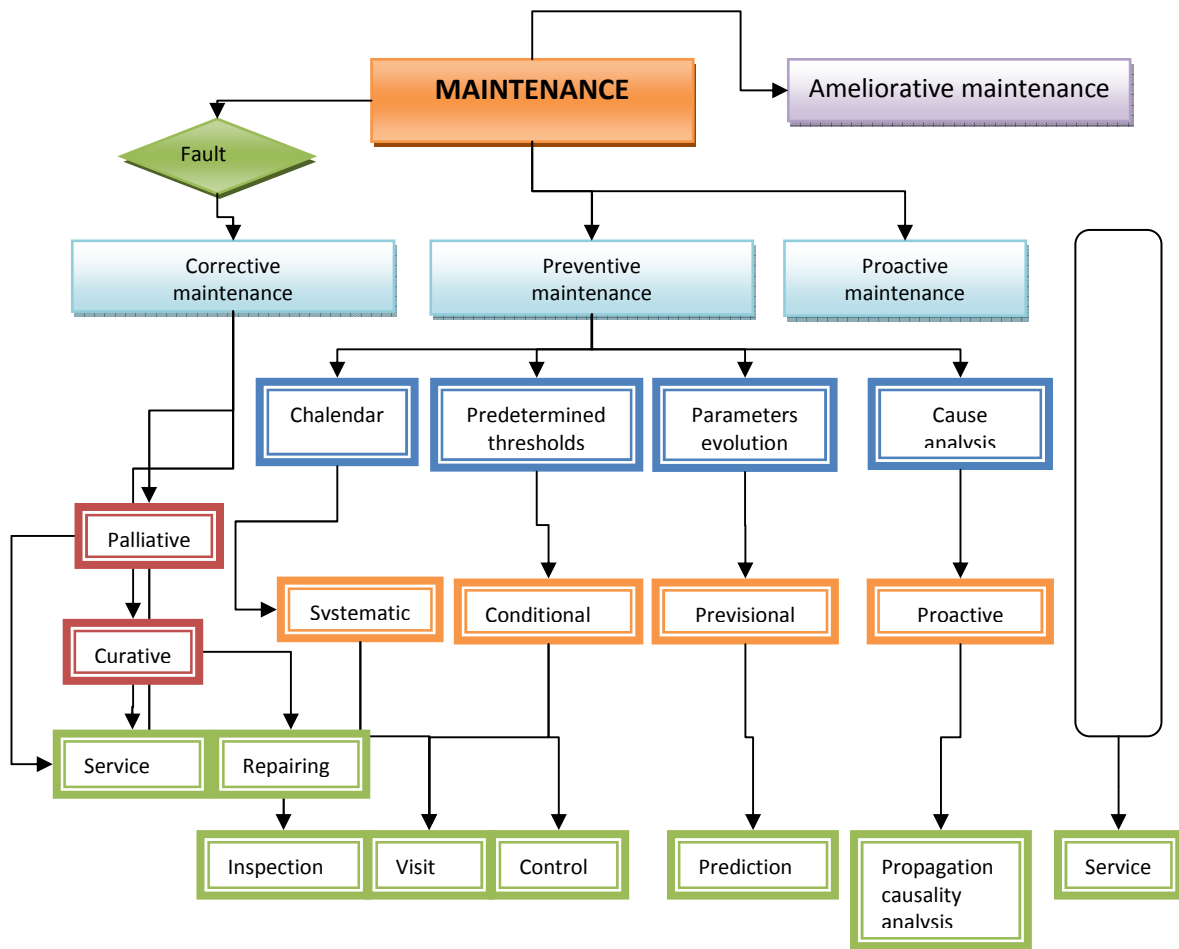
Figure 3. *Maintenance politics*

     ⊞ The '80s : Proactive maintenance (PRM)

Implies the continuous monitoring and verification of the primary failure causes for the monitored system

     ⊞ The 2000s : E-maintenance (Figure 2)

Observation

Given the importance granted to the propagation of certain faults/degradations as well as to the research of causes for their occurrence, our studies are positioned in the proactive maintenance area, with applications and developments that evolve towards creating distributed services, and, therefore, towards e-maintenance.

The current development of NTIC required the development of a real e-maintenance strategy. This prompted significant changes in companies' organization. There is a tendency to externalize the maintenance function, in order to maintain attention and concentration on basic activities or to transform classic maintenance into long-distance real-time maintenance. This is an important issue, in which monitoring plays an important role. The components of the monitoring systems are characterized by an increasingly greater autonomy, since they work in

distributed systems that often integrate embarked intelligence concepts ([Rac, 06]).

An essential element in industrial maintenance – both in its conditional, previsional, dimension and from the point of view of an efficient, structured, systematic feedback – is the monitoring that acquires a particular dimension due to the intelligent distribution of its functions, on the inferior hierarchical levels.

In the current context of automated production systems evolution and modern maintenance services, industrial monitoring evolves towards intelligent systems that integrate dynamic or even predictive dimensions due to the possibility for the intelligent exploitation of information developed in real time, which leads to an increase in its reactivity.

Chapter 2

Industrial monitoring

In a great number of industrial applications, we have noticed the tendency to replace the curative maintenance politics with preventive maintenance strategies. This may be explained by implementing certain production management strategies centered on the preventive control of situations with a potential for failure states occurrence, by using specific analysis techniques ([Rac, 06]). The monitoring function, based on the evolution of equipments capable of processing and classifying information acquired from the process, organized into consistent databases, succeeds to prevent failure or breakdown situations caused by a deficient functioning, before launching false alarms that might slow down the production [Bas, 96]. Many authors have approached the domain of industrial monitoring, which highlights the significant interest shown by the scientific community and the industry specialists with regard to these problems. Without claiming to have exhausted the papers written on the subject, we may mention the following: [Com, 91] [Dev, 91] [Tog, 92] [Pou, 96] [Cus, 96] [Evs, 98] [Web, 99], [Zha, 99], [Com, 00] [Lef, 00].

In the specialty literature regarding the industrial equipment monitoring domain, we find various definitions, which are sometimes even contradictory. For this reason, in the following chapters we resume parts of definitions and scientific explanations for the basic notions, so that we may demonstrate a well defined point of view.

2. 1. Classification of monitoring methods. Diagnostic problems

Monitoring techniques are generally divided into two groups: monitoring techniques *with and without a model* [Das, 00] (Figure 4).

Monitoring with a model is based on the existence of a formal model of the process, obtained by applying the formalization techniques offered by *Automatics* – [Com, 91].

Techniques of *monitoring without a model* are divided into two categories. The first category is based on statistic instruments applied on *Signal processing*. These are considered to be low level techniques, because they only quantitatively exploit the information offered through direct acquisition (information read by sensors). Thus, rough alarms will be triggered because, for the information supplied by direct acquisition, there is no apriori analysis of the acquired signals' significance [Bas, 96]. Therefore, the statistic instruments test the contexts with a potential for failure occurrence, but are not capable of explicitly ensuring their detection function. The second category includes the high level monitoring techniques that are oriented towards communication with an expert system. These techniques, based on the concepts of *Artificial Intelligence* (AI), serve as a basic instrument in implementing analysis and decision strategies. The answer is much more complex than the one supplied by applying low level techniques

because a complete analysis and decision context is created, by implementing the detection, interpretation and diagnostic functions for the faults that have occurred ([Rac, 06]).

Therefore, the two approaches supported by the Automatics/Artificial Intelligence domains may be combined in order to exploit their advantages, but also for conceptual complementarity reasons [Dub, 01]. The complementarity of these techniques categories is shown in [Dub, 94]. Moreover, some papers present the simultaneous usage of the two categories of techniques with interesting results in succeeding to implement complex monitoring structures: [Rac, 06], [Kat, 97], [Loi, 97], [Was, 98], [Hin, 95], [Vem, 97] [Vem, 98].
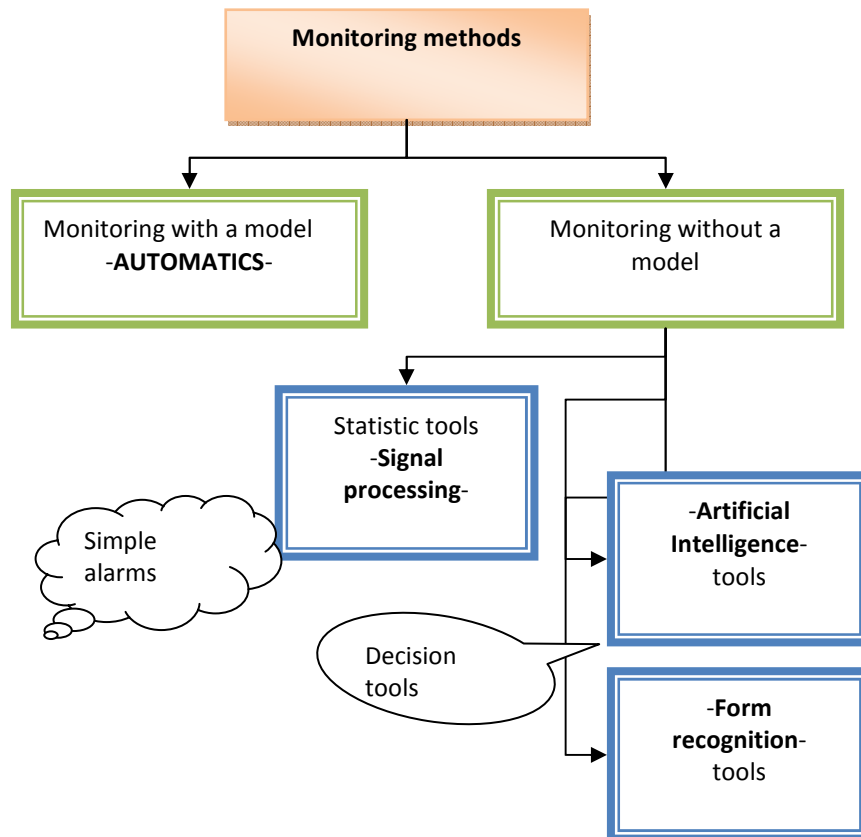
Figure 4. *Classification of monitoring methods*

When using Artificial Intelligence concepts, the monitoring function is often perceived as a form recognition application. The problem of form recognition has combined with the problem of automated image classification, along with the remarkable development of multimedia and Internet technologies. Extracting attributes or image descriptors represents the key phase, which emphasizes the recognition application's performances and professionalism. Choosing the most suitable attributes or characteristics is the key to success for recognition algorithms. The final result is a vector with n extracted attributes, which are not necessarily numeric. This represents the attribute vector, used as a reference input in the algorithm that implements the measured object or image shape membership to the image class, based on mathematical criteria or membership functions. The diagnostic function was formalized through shape recognition algorithms. A reference definition provided in [Dub, 01], [Rac, 06] proposes the following approach to the diagnostic function:

> *A diagnostic problem may be defined as a shape recognition problem. The number of states is equaled to the number of classes, while the form vector is the vector of the observed parameters.*

In the performed research, beside the monitoring function, we have also approached the diagnostic function, which is fundamental from the point of view of the final intervention action for the purpose of correcting the monitored process' efficiency. Apart from the passive aspect of the detection function, the research and identification of fault occurrence causes require the development and application of certain specific techniques, which can be identified outside the form recognition domain.

The etymology of the word "diagnosis" comes from Greek and it means: *Dia*: through, *Gnosis*: knowledge. Inspired by this, in [Pen, 90], we find an interesting formulation [Rac, 06]:

> *Given an observable manifestations context (symptom, findings, observations, etc), the diagnostic explains the presence and identifies the causes of their occurrence, by using a knowledge basis regarding the system taken into account.*

In our research, we accept this definition for the diagnostic function because it highlights the reasoning we need to follow in order to accomplish an "understanding" of the observed state. The approach is resumed in papers [Zwi, 95], [Gro, -a,01], [Bou, 95] [Bou, 95] [Bou, 03]. Moreover, the definition proposes the decomposition of the diagnostic functions into two other functions: localizing and identifying the cause. Since the diagnostic is based on observation, numerous authors consider detection as being a part of the diagnostic phase.

Starting from this definition, the diagnostic – as well as monitoring – treat numerical data (the result of observation materialized through measurements) and symbolical data (knowledge regarding the system taken into account).

In [Dub, 90] these two types of data are considered necessary knowledge in the diagnostic operation. On the one hand, it utilizes *global information*, those associated with the « apriori » knowledge of the system and responsible for its well functioning history. On the other hand, *the instantaneous information* corresponds to the quantity of knowledge corresponding to the present temporal section, necessary in making a decision and applying the correction function.

The definition of [Pen, 90] generated another approach that results from the exploitation of causal knowledge over the system's evolution. A «dysfunctionality» may be described through associations of the initial causes (process components' failure, etc) with the observable manifestations – symptoms of these dysfunctions. If we have a theory capable of modelling these relations, the diagnostic problem is reduced to finding « explanations » that satisfy the observed symptoms. The reasoning is based on the reverse road that goes from effects to causes, trying to attach plausible causes to a number of premises. This type of logical reasoning is called *abductive reasoning* ([Rac, 06]).

The abductive reasoning may be described as such:

Given a situation « B » to which we associate a causality relation " A $\rightarrow$ B " (" A " causes " B"), then the cause of B situation's occurrence is " A possible ".

This raises another important problem for diagnosis: to what extent may we consider the knowledge regarding the system, be it causal, global or instantaneous, as sufficient and what is the technique recommended for identifying and validating it?

Bearing in mind the complexity of this problem, many methods of describing the system

through information have developed, which utilize various techniques. For this reason, in the following section we suggest a classification of monitoring methods, starting from description criteria associated to the diagnosis.

2. 2. Monitoring techniques with a model

The method categories which are used most often in industry nowadays are usually functional and material modelling methods. These categories appeal to industrial tools of the type AMDEC (*Fr.: l'Analyse des Modes de Défaillance, de leurs Effets et de leurs Criticité)* and to the ADD (*Fr.: Arbres De Défaillances*) faults tree (FT), mostly used in diagnostic ([Rac, 06]).

— ***Diagnostic methods through functional and material modeling***

> *The principle of these methods lies in the apriori and most complete possible establishment of the causal relations between the initial causes of the faults and their measurable effects. The methods applied most often are AFMEC Analysis and FT Analysis.*

Another method in the model monitoring category is the one based on the physical modelling of the monitored process ([Rac, 06]).

— ***Monitoring methods through the physical*** modelling ***of the system***

> *Monitoring methods with a physical model are based on the comparison of measurements performed on a set of process parameters with the information supplied by the associated model. Any noted abnormality will be considered a fault or a malfunction. Dedicated tools subordinated to the concepts of decision theory are used to establish if these abnormalities are generated by normal disturbances or are caused by the occurrence of certain faults in the system. Monitoring methods based on a model are most familiar to automatics specialists. In general, these can be separated into two categories of techniques: physical and analytical redundancy techniques and parametrical estimation techniques, presented in detail in the following papers: [Wil, 76], [Ise, 84],[Bas, 88], [Bas, 93], [Ger, 88], [Ger, 98], [Pat, 89], [Fra, 90], [Com, 91], [Cus, 96], [Web, 99], [Tro, 00], [Com, 00], [Plo, 01] as well as [Zem, 03].*

2. 3. Monitoring techniques without a model

Monitoring techniques without a model were generated by the complexity of industrial applications, which made it impossible to identify a usable coherent model ([Rac, 06]). For this type of industrial applications, operational monitoring functions were used: monitoring based on signal processing statistical tests and monitoring based on concepts specific for artificial intelligence [Dub, 01].

— ***Monitoring based on signal processing statistical tools***

Fault detection statistical tools start from the hypothesis that signals supplied by sensors contain statistical properties. Repeated tests allow the examination of a measured signals sample's appurtenance to these statistical properties. A great variety of tests, applicable to measurement samples, may be found in [Bas, 88]. The tests either quantify the exceedance of reference values (threshold), or test the mean or variation of measured signals [Zem, 03].

— ***Monitoring through Artificial Intelligence symbolic*** modelling ***methods***

In an initial approach, this method category separates the diagnostic techniques into the following categories: diagnostic through form recognition subordinated to a probabilistic approach, fuzzy approach diagnosis, neuronal approach diagnostic [Dub, 01]. This classification is a bit restrictive, if we take into consideration the numerous researches in the domain of monitoring without a model based on Artificial Intelligence (AI) concepts. The methods work with symbolic knowledge (logical formalism) but also with eclectically expressed information: verbal phrases, directly perceived sensory information, mental images, experiences, hypotheses, etc. that can easily be divided by the operator [Bas, 96]. AI methods may be characterized by their capacity to treat ([Rac, 06]):

- o a great quantity of information
- o heterogeneous data (numeric/symbolic)
- o context-dependent data
- o incomplete data

These methods may be regrouped in « *Symbolic* modelling *methods* » (Figure 5). In the specialty literature, there are numerous researches that result from the associative-predictive-explicative approach (INRIA) [Bas, 96] and the degraded pannes functioning operational-model form-model recognition approach (IRISA) [Agh, 98]. A wide presentation on this matter is offered by the [Mon, 04]. The classification we propose regroups the methods presented above with clear definitions for each of the three indicated methods ([Rac, 06]).

Due to the difficulty in offering a clear and synthetic definition to diagnostic methods, we propose their characterization through key words that offer suggestive information about the objectives and particularities of each approached method. In the area of symbolic modeling, three typologies may be distinguished: behavioral models, form recognition models and explicative models ([Rac, 06]).

Methods based on behavioral methods

> *These methods are based on simulating the system's behavior, starting from the model associated to it. In most cases, a well functioning model is elaborated, which, unlike numeric models, is not based on monitoring physical measures of the system, but rather on considerations regarding the manner of functioning, the evolution of the states, etc.*

These methods regroup the following tools: Petri Nets and finite state automata, and they will be characterized by the terms *modeling/simulation*.

Form recognition methods

> *This method regroups the associative models and the recognition models, in the sense that they can perform classification, instruction and recognition functions. The recognition mechanism is efficiently applied both to form recognition systems and to expert system-type rule bases systems.*

Tools based on general form recognition concepts are: form recognition statistic methods, neuronal nets, fuzzy logic, neuro-fuzzy nets, expert systems. The key words that best describe this approach are *instruction/recognition*.

Methods based on explicative methods

> *These methods are based on the notion of explicative models introduced by [Bas, 96] and include in their definition mostly models that describe the failure states [Agh, 98]. They supply the causal analysis of relations between faults, causes and their observable*

    effects.

Within these methods, we take into consideration the applications based on the following tools: influence graphs, contextual graphs, Petri Nets and fuzzy logic. The key words are *causal analysis.*

Figure 5 illustrates this classification [Mon, 04] in the general context of symbolic modelling tools classification through AI techniques ([Rac, 06]):
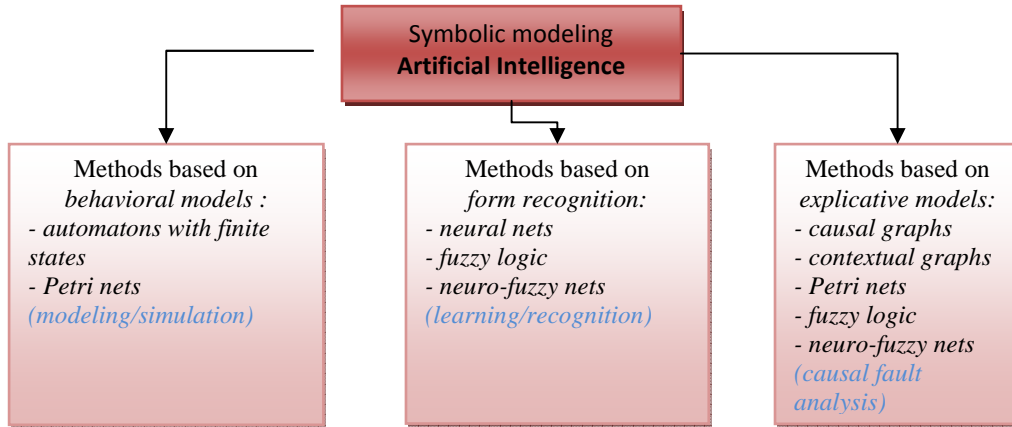
Figure 5. *Classification on monitoring tools based on AI techniques*
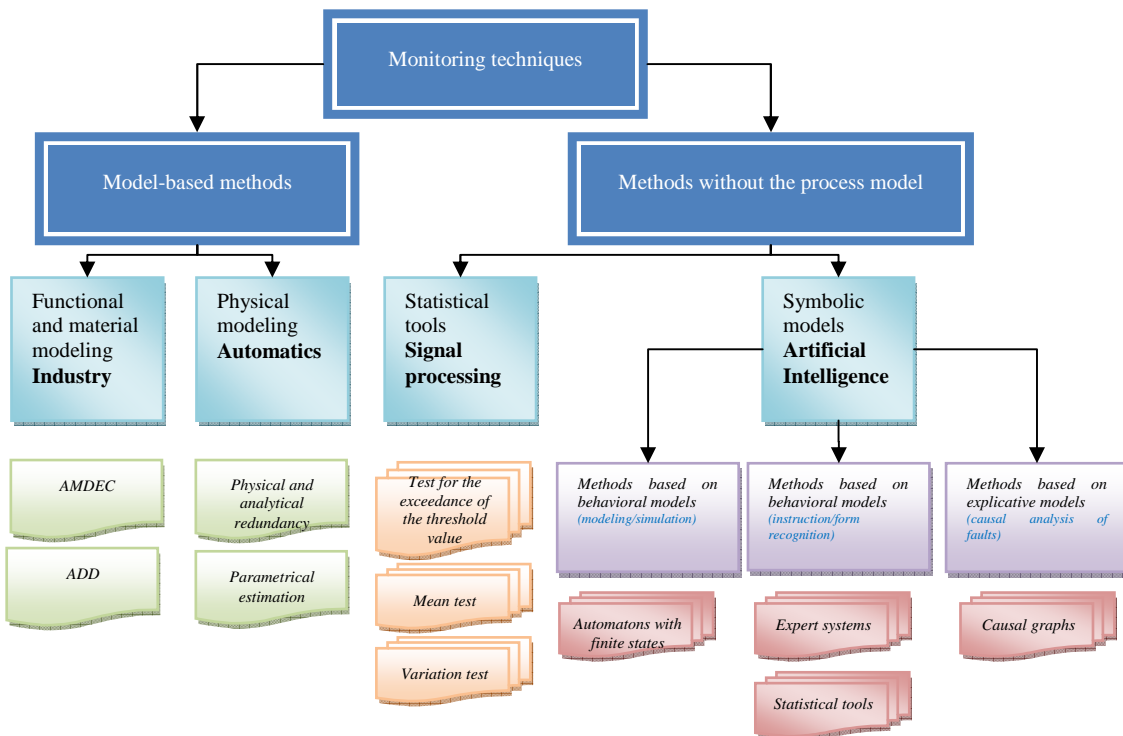
Figure 6. *Global classification of monitoring methods*

In the light of the proposed classification and given the importance and specificities of the diagnostic function, we obtain an overview on monitoring methods, synthesized in Figure 6.

Since the research presented in this paper was channeled towards symbolic modelling with Petri Nets, the following chapter will make a short presentation of PN tools used in the development of monitoring applications based on behavioral models, mostly those dedicated to the diagnostic function modeling. The presentation analyzes these PN-type behavioral models with relation to the diagnosis, with relation to the definition in [Pen, 90] or with relation to very detailed information introduced in DEA by M. Monnin [Mon, 04].

2. 4. Petri Nets for monitoring functions modelling

According to the approach proposed by [Com, 91], the monitoring/command system is modeled through two *Oriented- Object Petri Nets* (*OOPN*) [Sib, 85]: the PN reference model and the PN command model (Figure 7, Figure 8).
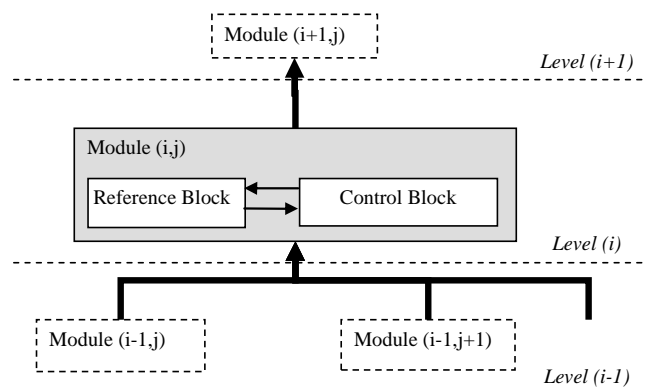
Figure 7. *Reference model control*

These models cooperate towards the satisfaction of global restrictions imposed on the process. The originality of the proposed approach is based on the observation that restrictions may be divided into two independent categories and will be adequately represented through different *PN* tools:

  ⊕ restrictions that translate the real state of the physical process will be described in *the reference model*;

  ⊕ restrictions imposed on control, in accordance with the functioning/action restrictions imposed on the monitored system. They contain sequences of execution operations, associated to the particular usage of the process, in conformity with the manufacturing range specific for a certain process. These restrictions will be described in *the command mode ;*

Modules positioned on the same level correspond to the macro-commands represented by independent modules. Each level contains a number of modules that represent the granularity of the model, according to the abstraction level chosen for each activity. The hierarchical structure requires a hierarchical authority in the circulation of information fluxes. The orders are created in the highest levels and are reflected on the subordinated modules situated at the base of the hierarchy. The information moves upwards in an ascendant flux, whereas the decision request descends the structure through sub-decisions formulated by modules situated on the descendant levels.

At the level of each module, the PN reference model the restrictions imposed on the command.

After the performance of the corresponding activities (common nodes with a collaborative aspect) the command system will always find itself in one of the usable states. The procedure's model serves as a command database, but also as a detection and diagnostic basis. The net respects a hierarchical structure created through an ascendant endeavor and by applying an abstraction algorithm.

The abstraction must not restrict the process' usage possibilities. A high detail degree leads to a complex reference model, but at the same time rigid and slow in elaborating requests towards inferior modules. On the contrary, a high abstraction level leads to the loss of information. Certain usable states become forbidden due to the simplified reference model, which leads to the elaboration of false commands. From the point of view of command, the PN reference model contains information that validate or invalidate the command elaborated in the command net due to the complete model of usable states that it imposes. The two PN models are collaborative, in the sense that they only evolve if the conditions imposed in the junction points are fulfilled (Figure 8).

The occurrence of an event that modifies the state of the command (Pcom) is translated into the command net in two transitions, which represent the beginning and end of the command (Tdeb_com, Tfin_com). Each of these transitions is separated in two (Tdeb_com1, Tdeb_com2 and Tfin_com1, Tfin_com2) in order to initiate the collaboration mechanism between the two models. In Figure 8, the dotted arrow represents the synchronous and collaborative evolution of the two models in the nodes that contain common actions. Each reference module is not directly linked to the corresponding modules on the same level. It is only in an inference relation with the command net modules. This highlights the cooperative relation of the two models and, at the same time, a refined representation of each macro-activity, up to the level of elementary activities.

In other words, the command net implements the control of the production system, therefore it models the restrictions specific to the manufacturing range of a certain product, as well as the temporal and material restrictions imposed by authorization. The command net conception proposes a descendant endeavor and will be based on the principle of successive refinement.

Simplified representation of both PN collaborative models
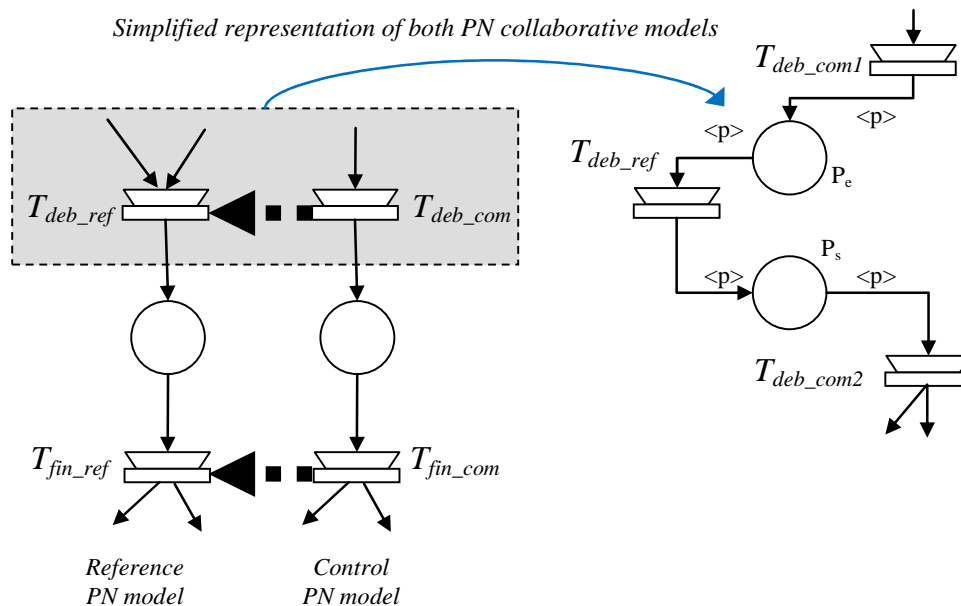
Figure 8. *Communication mechanism between the reference and control PN*

Communication mechanisms

In the presented approach, the monitoring function is decomposed into active monitoring sub-modules (Figure 9). Each module contains all the elementary components of the monitoring function, which are responsible for the well functioning of the process: detection, diagnostic as a correction function or the extreme-urgent form. The interface module with an operator allows its intervention in the case of a conflict or « unknown » situation from the point of view of implemented fault states classification.
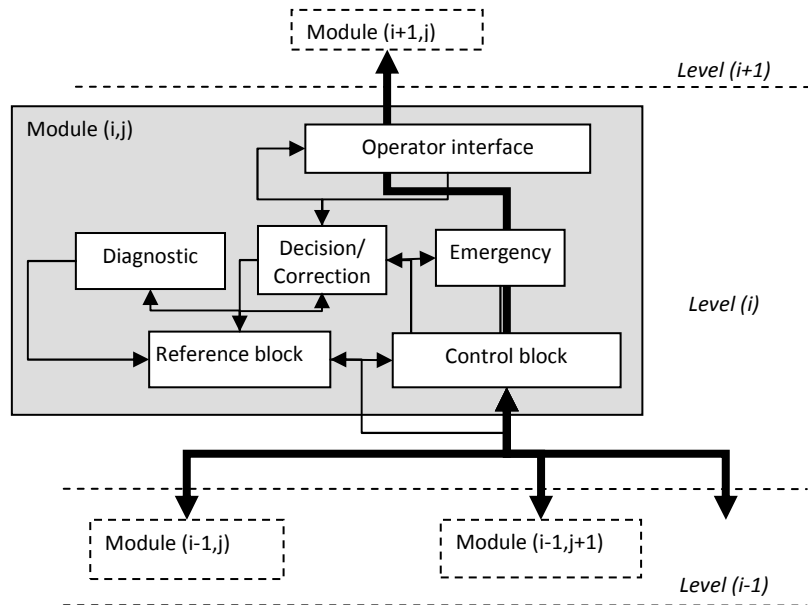
Figure 9. *Monitoring/command module*

In the proposed approach, we consider the hypothesis that the process model is a component of the monitoring function model. On the one hand, this represents a complement of the detection function implemented through the number of action sensors/elements placed at the lowest level. Direct detection is insufficient due to the limited number of sensory elements that can be used, compared to the multitude of faults that might appear during functioning. These two mechanisms allow the identification of material faults trough "abnormal feedback signals"(CR) (*fr: "les comptes rendus anormaux"*) and/or an operation's execution delays (as a result of a current fault or one that has already occurred).

The communication between two PN models lies in the emission of requests from the superior level to one of the inferior modules or in the return CR signals emission that ascend in reverse. Each request issued towards a module will return a dual CR to the superior module that issued the request.

The mechanism is similar to the one in which a module informs the unique superior module that the command has been accomplished. This approach was developed by assuming that the command system functions correctly, and the faults are only visible in the physical system, therefore in the net found in the reference for the command net. Communication between the two nets is always initiated by the command net (Figure 8).

The command modelling is performed with *Oriented-Object Petri Nets* [Sib, 85](*OOPN*) which introduces a specific concept in the generic modelling of the events: the jetton is associated to

attributes that must verify the preconditions and postconditions associated to the transitions T_deb and T_fin. Validating these transitions leads to the modification of attributes according to imposed attribution rules. In modelling *OOPN* (Figure 10) an activity is performed if the conditions associated to the activity beginning and end transitions are fulfilled.
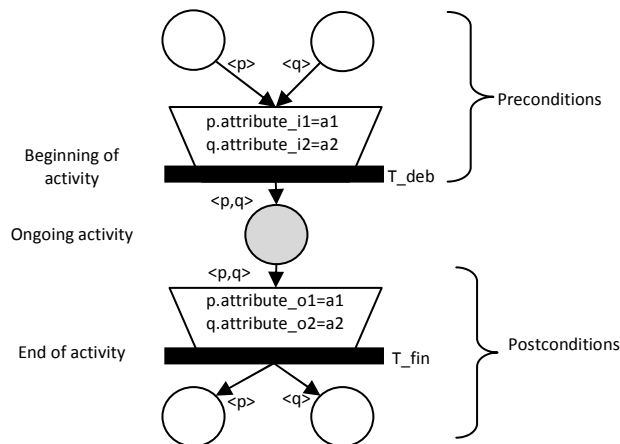
Figure 10. *Modelling an activity with OOPN*

2.4.1. Detection

The detection of an anomaly is performed by activating an analysis mechanism implemented during the process monitoring. This mechanism must be capable of emitting a fault symptom in order to signalize the absence of CR signals or of receiving abnormal CR signals. The detection implemented in this approach (with a reference model) is based on two mechanisms [Com, 91] and [Bon, 93]:

- WD « watchdogs » signals
- CR return signals

These mechanisms lead to two different approaches for the detection function:

- *direct detection* is based on information gathered by sensors and comparing them with the expected values. If a signal is missing or registers a delay in its emission/reception, direct detection emits a warning which announces the failure state.

    Observation: the original approach to system monitoring presented in this paper proposes a treatment for these situations and temporal aspects that intervene in the analysis of the failure states.

- *indirect detection* performs the hierarchical and gradual analysis of the CR return signals. These translate a behavioral anomaly of the system when the reception of the CR signals is situated outside the temporal windows associated to the normal functioning state.

2.4.2. PN model for the detection system fonction

The WD (*Fr.:* « chien de garde ») mechanism is available in ordinary PN but can also function in *Oriented-Object Petri Nets* (*OOPN*) and *Temporal Oriented-Object Petri Nets* (*TOOPN*). *OPN* works with classes of objects organized in an arboreal form [CAR, 90], a class of variables and a class of positions that are in a bijective relation with the class of objects [CAR, -a,-b, 96] (Figure 11a).

OPN associates each transition with a conditional Boolean logical expression. Moreover, each transition is associated with a number of tasks that correspond to events associated with each of them. As an example in Figure 11b), the state P_3 will only be marked if t_1's preconditions are validated. Transition t_2, a successor node for position P_3, will be validated when its (P_3) precondition becomes true.

Temporal Oriented-Object Petri Nets (*TOOPN*) [Sib, 85] associate certain transitions to a temporal window in which we can perform its shooting, as soon as it is validated.
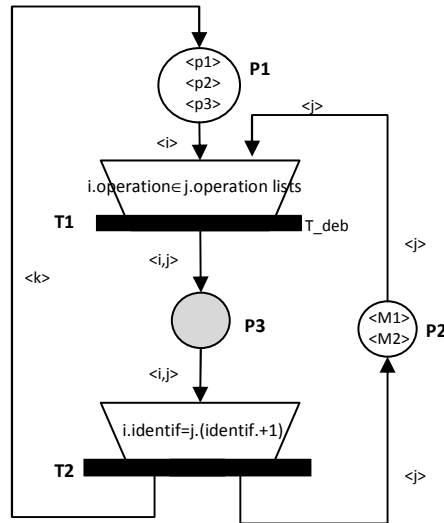
Figure 11. *Temporal Oriented-Object Petri Nets – TOOPN*

Object classes:	Position classes:	Variable classes:
PIECE	p1 : PIECE	I : PIECE
identifier	p2 : MACHINE	J : MACHINE
operation	p3 : <PIECE, MACHINE>	
MACHINE :		
identifier		
operation		

Between two events connected by a causal relation, we may implement a mechanism based on an explicit temporal restriction. Each transition can be associated with a WD signals that will be « used » by the diagnostic if a transition exceeds the preordained value of the duration in which it can be crossed. Using *TOOPN* in monitoring modelling allows the association of an interval [Tdeb, Tfin] to each transition (Figure 12).

The limits of this interval represent the firing conditions of the transitions, added to the firing conditions imposed on the jetton's attributes. The time variable appears as an attribute of the jetton relative to the moment of the transition's execution. If the jetton in the P position is delayed until moment T_{deb}, it becomes susceptible of being « eliminated » in the interval [T_{deb}, T_{fin}], through the TG transition. At the moment θ (in the interval $[\theta_1, \theta_2] = [T_{deb}, T_{fin}]$), the TG transition is crossed if all its preconditions are validated.
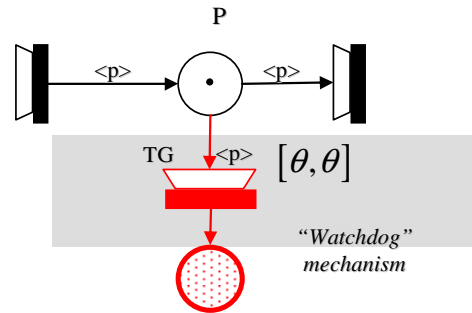
Figure 12. *The « Watchdog» mechanism (fr : «chien de garde »)*

During detection, the WD mechanism is implanted into the reference net in order to model an anomaly translated by the apparition of a failure symptom. One of the hypotheses of this approach is the perfect command (without anomalies). In Figure 13, Symptom 1 expresses a lack of resources for the normal debut of the activity, whereas Symptom 2 indicates a lack of CR that would make the reference net advance. The WD mechanisms will be used in a distinct net conceived to evolve in parallel and in real time with the monitored system. This will be possible by implementing a specific mechanism, known as "*token player of PN*" (fr: « *le joueur de réseau de Petri*») (Figure 14). The detection function will be implemented through WD signals a temporal mechanisms. The fuzzy aspect of detection, and implicitly of monitoring, will result from the fuzzy modelling of the temporal window associated to TG transitions.
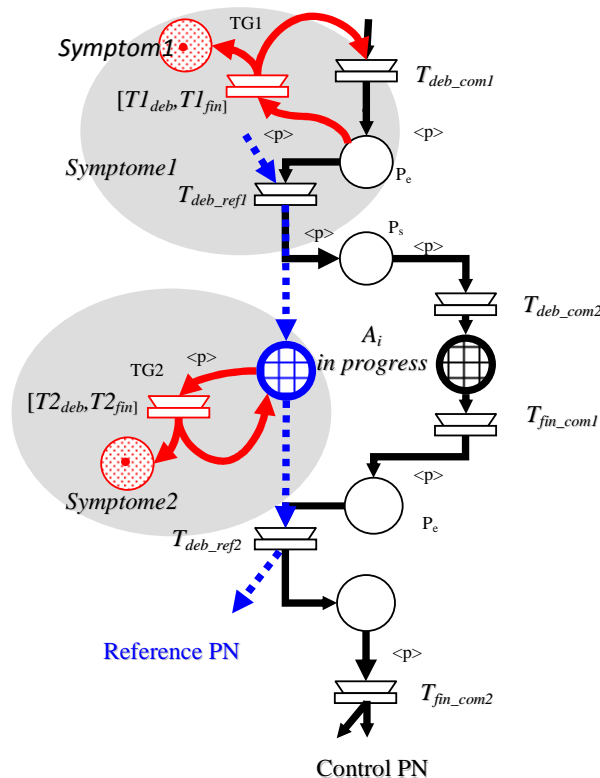
Figure 13. *« Watchdog » mechanisms for direct detection modelling*

2.4.3. Diagnostic – decision

The task of the diagnostic function is to elaborate explicative information with regard to the

anomalies produced inside the system. The main purpose is to determine the origin of the faults and to identify the causes responsible for the detected anomalies. The mechanism of the diagnostic function requires complementary information able to describe the state of the process at the time when the failure symptom appeared as an active sequence at the moment when this anomaly occurred.
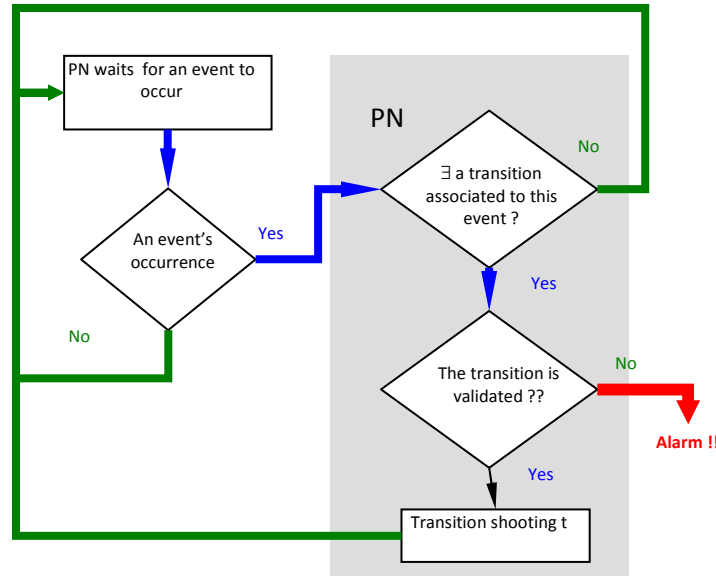
Figure 14. *« Token player » mechanism in an RP*

The current research in diagnostic modelling highlights different diagnostic systems typologies that are more or less efficient. The expert systems describe, as logical rules of diagnosis, an operator's or an expert's experience in identifying the causes of a number of faults occurrence. These systems can identify, through inference rules, the relation between a fault's occurrence and the informational context that characterizes the state of the real system.
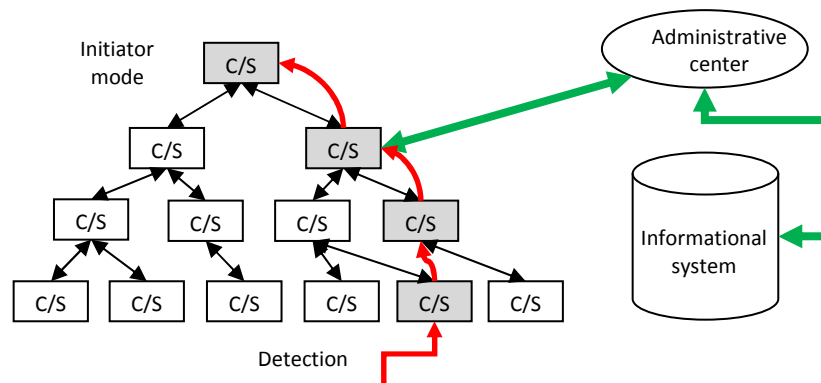
Figure 15. *The general structure of the monitoring system*

In the LAAS approach (*Laboratoire d'Analyse et d'Architecture des Systèmes*) [Com, 91] the monitoring/command system's structure is hierarchical and modular. Each module possesses its own command and monitoring functions (Figure 15). The detection function is integrated into the command module, whereas other functions are distinct and structurally integrated into the monitoring system corresponding to each module.

When it detects a fault, the module that signaled the failure symptom - called initiator module [Cha, 95] - tries to identify the cause of this anomaly, appealing to its own diagnostic function. It can only take action if it possesses enough information to find the cause of the occurred fault. If not, it sends a request towards the superior hierarchical level, so that a diagnostic may be found [Bon, 93].

Chapter 3

Fuzzy Petri Nets. Application in dynamic monitoring

3. 1. Introduction

The presented techniques in the previous chapter indicate a remarkable interest towards monitoring centered on Artificial Intelligence symbolic modelling methods. To this effect, the fuzzy expert systems exploit an uncertain knowledge basis, modeled through a rule basis. The usage of fuzzy logic in monitoring allows the refinement of information acquired by direct detection (information acquired directly from the field). This refinement is realized by introducing « the degree of truth » (a real number between 0 and 1) associated to each variable/sentence/logical phrase so that, considering an ensemble of specific rules (most often evolutive), we may describe the dynamics of a process in terms characteristic to a human expert's manner of thinking. This approach is promising due to the significant potential in the modelling of dynamic monitoring and of the prognosis function, by exploiting the results of repeated experiments through which the human factor can identify the traceability of the corrective actions, at the level of the intuitive action, based on his experience.

Therefore, the development of an original Fuzzy Petri Nets (*FPN*) (*fr:* les réseaux de Petri flous) tool dedicated to the modelling of DES systems' dynamics in a fuzzy approach, allows the consideration of uncertainty factors associated to the model's states and transitions, but also the validation of the entire *FPN* model through an informatics tool capable of integrating elements specific to fuzzy logic.

The *FPN* tool, whose originality we claim, is oriented on monitoring and repairing DES systems with particularization on production systems. The model is implemented in an informatics tool, so that the user interface allows the return of information in a system-monitoring-control loop. In industrial maintenance, this loop is used as a tool specialized in decision making. The integration of fuzzy logic into such a system, with a decisional structure, allows the formalization of the human factor's exploitation experience, for the purpose of developing a predictive dimension.

3. 2. FPN tools in process monitoring. Application in dynamic monitoring

Fuzzy logic allows the representation of approximate logical reasoning that intervene in the description with a certain factor of uncertainty of uncertain, imprecise knowledge, of

experimental and practical information. These aspects that quantify «the degree of truth» cannot be described with the techniques of classical logic.

Petri Nets used in the monitoring and control of DES systems may easily represent activity synchronizations in collaborative PN models. Once the time is integrated, the PN model belongs to the category *temporal* or *temporized Petri Nets* – tools that can be used to easily model direct and indirect detection (through WD and CR mechanisms). Once we find a way to represent the fault's propagation process dynamics in the structure of the faults tree (FT), and once we integrate the fuzzy logic in aspects that quantify through fuzzy temporal variables the occurrence and gravity of a fault, we manage to create an PN tool specialized in the fuzzy modelling of monitoring functions.

Significant research in the domain of Fuzzy Petri Nets have proposed the modelling of approximate arguments, starting from a static logical rules concepts [Loo, 88], [Che, 90]. For this reason, in order to create the dynamic aspect of process monitoring, we propose the *Monitoring Fuzzy Petri Nets (MFPN)* which, by definition, integrate the *fuzzy temporal* aspect.

3. 3. Fuzzy Petri Nets. Present stage. Fuzzy Petri Nets usage in DES systems monitoring

The fuzzy approach to systems monitoring allows qualitative descriptions of process variables, through fuzzy logical variables and through the associated truth degrees that belong to the interval [0,1]. The tool which is able to model DES systems' fuzzy monitoring must integrate generic modelling concepts for an DES system, but also general fuzzy logic concepts [Rac, 06].

The first contributions to logical rules sets modelling correspond to the generic modelling approaches of *production rules* through PN tools [Zis, 78], [Val, 87]. On the other hand, the research of [Mur, 88] models Petri Nets' dynamics by logical programming (Oriented-Object Petri Nets) [Sib, 85]. The token is an object with specific attributes and methods. These two directions allowed the development of an original tool, capable of integrating fuzzy logic into the Petri Net's structure.

Fuzzy Petri Nets (*FPN*) are a tool dedicated to the study of SED systems described through uncertain knowledge. The presentation of the existent approaches' current stage was published by Cardoso, Valette and Dubois [Car, -a, 96]. The first contribution belongs to Looney. Even though his approach is close to neuronal nets, his model's dynamics respects concepts of Petri Nets dedicated to fuzzy logic arguments. Subsequent to Loney's research, a few FPN-typologies approaches have developed, starting either from ordinary *PN* [Che, 90], [Ped, 94], [Lip, 94] or from high level Petri Nets [Sca, 94], [Gom, 98], [Gom, 95], [Cam, 98].

In the *FPN* category, according to the used logical classes (classical, linear, fuzzy), we distinguish two categories of *FPN* typologies:

- The first category is represented by *PN* tool specialized in the modelling of fuzzy logic arguments, expressed through fuzzy rules associated to descriptions of SED systems dynamics. Fuzzy rules describe production rules [Val, 87] [Val, 94] and are related to the model's transitions. The global model corresponding to the number of production fuzzy rules becomes a fuzzy expert system. In this case, *FPN* is interfaced with the real system which is monitored by direct detection (the information is supplied by the sensors). The transitions model the number of rules and will be validated and executed simultaneously. The output variable will have the truth degree supplied by defuzzyfication [Han, 94], [Gom, 95]. We recognize the mechanisms specific for a fuzzy

controller which, related to a fuzzy expert system, presents a very simplified typology.

— The second *FPN* category models the dynamics of a physical system. We obtain classes of applications that express the uncertainty of knowledge associated to the system resources' states [Car, 90], [Val, 89]. This *FPN* typology models a physical system through linear applications implemented to resources' state transformations. Linear applications preserve the uncertainty of knowledge relative to their availability.

		Looney	Chen&al.	Bugarin&al.	Konar&al.	Scarpelli&al.	Cardoso
Logical rules bases	Imprecision	No	Numbers of fuzzy rules	Numbers of fuzzy rules	Numbers of fuzzy rules	Numbers of fuzzy rules	No
	Uncertainty	Credibility degree [0,1]	Truth value	No	Truth value	No	Credibility degree [0,1]
Fuzzy Petri Nets	Replaces imprecision?	No	Positions, tokens	Positions, tokens	Positions, tokens	Positions, tokens	No
	Replaces uncertainty?	Transitions, tokens	Transitions, tokens	No	Transitions, tokens	No	Transitions, tokens
	Evolution rules in the theory of Petri Nets	No (Looney modified the simple transition law)	No (The definition of the evolution rule for intermediary states is not consistent)	Yes	No (The modifications supplied by Looney were adopted)	Yes	No
Implementation algorithm	Is it consistent with the fuzzy rules basis?	Yes					
	Is it conformable with the execution proposed by Petri Nets?	No (according to the modifications of the transition's execution rule)	Yes (except for the intermediary states that can only have one input arc)	Yes (the net's structure and algorithm depend on the initial marking)	No (according to the modifications of the transition's execution rule)	Yes	Yes

Table 1. *Different approaches for FPN*

The components of *FPN* are adapted to the knowledge representation through fuzzy variables (fuzzy numbers and membership functions) associated to positions [Cao, 93], [Bug, 94], and/or transitions, and/or jettons [Che, 90], [Ped, 94], [Lip, 94], [Sca, 94], [Gom, 95], and/or markings [Car, 90], [Car, 95], [Val, 89] and/or arcs [Cam, 98], [Lip, 94]. In all approaches, the presence of the token is binary, even though it is associated with the truth value in the moment of its apparition in position.

Therefore, in order to preserve the coherence of the *FPN* models with the number of equivalent logical rules (the monotony of classical logic), we propose the following observation:

– In each transition, there is an infinite number of jettons.

– A transition's firing reinstates the token in the place that belongs to its predecessor set of places. The infinite number of token will not be modified ($\infty - 1 = \infty$) after its firing [Mur, 88], [Card, -a, -b, 96].

3. 4. General concepts in FPN monitoring

Fuzzy Petri Nets are oriented towards the modelling of fuzzy logical arguments, but based on the static logical rules concepts [Loo, 88], [Che, 90]. In order to describe the dynamic aspect of systems monitoring, we propose Monitoring Fuzzy Petri Nets (*MFPN*) based on a *fuzzy temporal* approach.

Hypotheses:

– The monitored system is modeled through two typologies of *Temporal Oriented-Objects Petri Nets (TOOPN)* [Com, 91]. One of the models describes the normal functioning of the material system – *Reference Model*. This serves as reference for the control model – *Command model*. The two models are in a collaborative relation (Figure 17)

– We imagine the existence of the system's model (Figure 16). The model includes *direct detection* [Lef, 00], which lies in the occurrence of the faults symptoms signaled by the monitoring system's sensors [Com, 91]. On the other hand, in order to refine detection, we imagine that the system also contains indirect detection. Direct detection corresponds to functioning sensors and elements, positioned so that they may supply information about the activity's beginning/end (intelligent sensors).
– *The detection function* is modeled through *TOOPN*. One of the token's attributes is the transition's « *firing instance*».
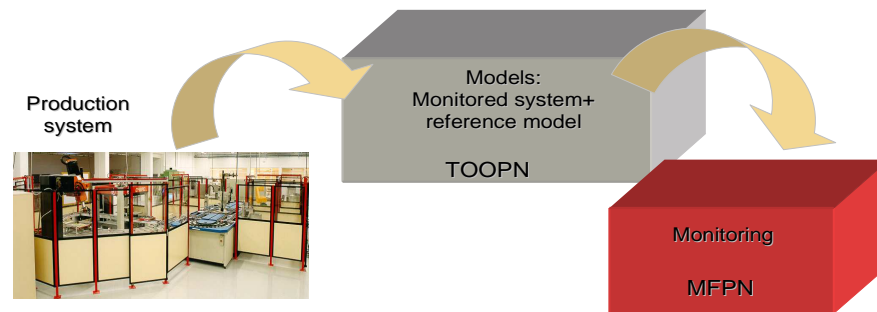
Figure 16. *Flow chart of the monitoring/control system*

The performance of the activity A_i imposes the initiation of the command ((Tdeb_com1, Tdeb_com2) and the inspection of the physical resources' availability (Tdeb_ref). If no faults are signaled, the action will be performed in the real system (*a_i in progress* – in the reference model) while the command is being performed. The finalization of the command (Tfin_com1, Tfin_com2) associated to the transition Tfin, rechecks the availability of the physical resources.

FPN temporal aspect. In a fuzzy approach, a transition is associated with a sensibilisation period θ[Mer, 74]. The token that reaches the moment τ for its input position, may cross the transition T_1 if the delay of its stay in the input place does not exceed θ. Thus, it will cross the ordinary transition T_2 which is associated to the sensibilisation interval $[0, \infty)$.
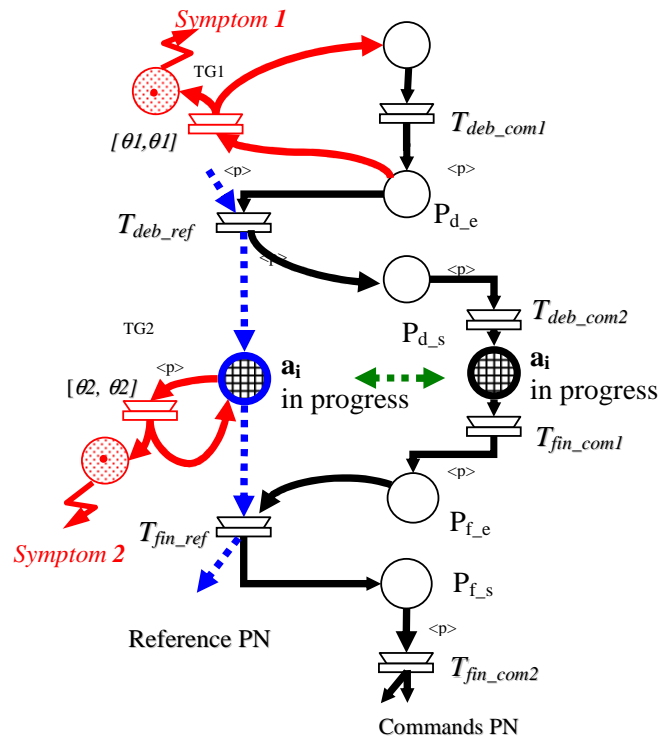
Figure 17. *TOOPN for monitored system modelling. Direct detection*

The firing moment of transition T_1 may be described as included into a temporal window $[\theta, \theta]$, associated to T_1 transition. The transition waits for the delay of the token out of range $[\theta, \theta]$, which leads to its "confiscation". The « *watchdogs* » mechanism models the anomalies of the monitored system in this way. The delay of the token's stay (the token blocage) explains the lack of resources availability in the reference model or the early or late debut of the activity in progress. Thus, at the moment $\tau + \theta$ a fault Symptom will be delivered. The token that crossing TG transition will have attributes modified by the references of the failed activity (Figure 18).
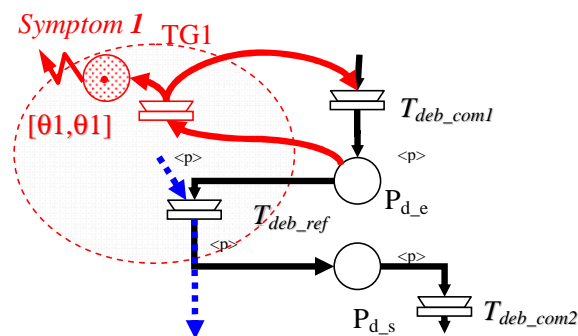
Figure 18. *Modelling a fault that occurs at the debut of an activity*

The control PN model is associated to such mechanisms that might indicate a faulty activity. Its mechanism is based on the collaborative relation between the two models: reference and command. The potential anomalies stop the models' evolution by the WD mecahnism who

"steal" the token. A fault Symptom is then emitted. By convention, the marked place which is a post-condition for TG is called a *Symptom*.

In Figure 18 the command associated to T_{deb_com1} transition is emitted at the moment τ. The WD mechanism checks if the system is functioning normally. The transition T_{deb_ref} is "consulted" in order to validate a correct activity debut. Having an *OOPN* structure, the token checks, through the attributes associated to it, the conditions imposed on $T_{deb\_ref.}$. This transition has the sensibilisation interval $[0, \infty)$. If all conditions imposed on the jetton's attributes are validated, the transition will be executed. If not, the jetton will cross the WD transition, immediately followed by the issue of a fault Symptom.

In the definition of Temporal Petri Nets, the temporal aspect may be treated in two ways: either a *sensitization period* θ is imposed for the transition, or *a sensitization interval* [a, b] is imagined. In this case, the TG transition will be associated to the interval $[\tau,\tau+\theta]$.

□ **The refinement of the detection function in a fuzzy approach**

The approach presented (Figure 18) has limits with regard to the information's refinement. A Symptom may be generated through:

■ A displaced command (very premature, very late *; fr:* beaucoup plus tôt ou beaucoup plus tard)

■ A fault in the reference PN if the token's attributes do not respect the imposed conditions

With respect to the execution time of an activity, the following hypotheses are imposed (Figure 19):

– An activity's duration $A = [T_{\min}, T_{\max}]$
– The activity's debut may occur in the interval $Tdeb = [DEB\_pre, DEB\_late]$
– The activity's ending is possible in the interval $Tfin = [FIN\_pre, FIN\_late]$
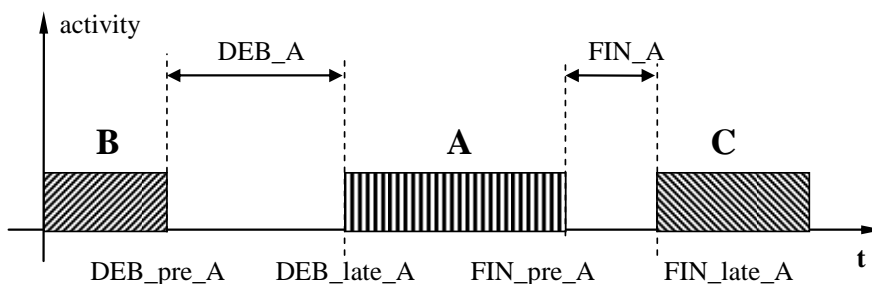
Figure 19. *The activities' planning*

The refinement of detection is imposed by an efficient monitoring system. The information supplied by the sensors as a result of direct detection will be used either in the diagnosis, in order to identify the causes of faults, or by the preventive maintenance that requires the prognosis of possible critical states.

We have presented the fuzzy modelling of an activity's duration (Figure 19) with a normal progress in the interval [DEB_pre, DEB_late, FIN_pre, FIN_late]. The fuzzy modelling proposes three types of possible faults:

— The late debut of the monitored activity (D_DT) which has the significance of a temporal desynchronization in the availability of physical resources

— The more than late debut of the monitored activity (D_DPT) which signifies that the system is in one of the prohibited states

— A failure occurred during an activity in progress, which will induce its much delayed ending fault (D_FT)

The debut before DEB_pre is not interesting to quantify, so long as the end of the activity is verified. In Figure 21 we have represented the WD mechanisms dedicated to monitoring these faults. Two WD mechanisms monitor the activity debut (in the sense of acceptable delays). The TG1 transition verifies the very late debut, whereas TG2 may signal the late debut of the fault limit.
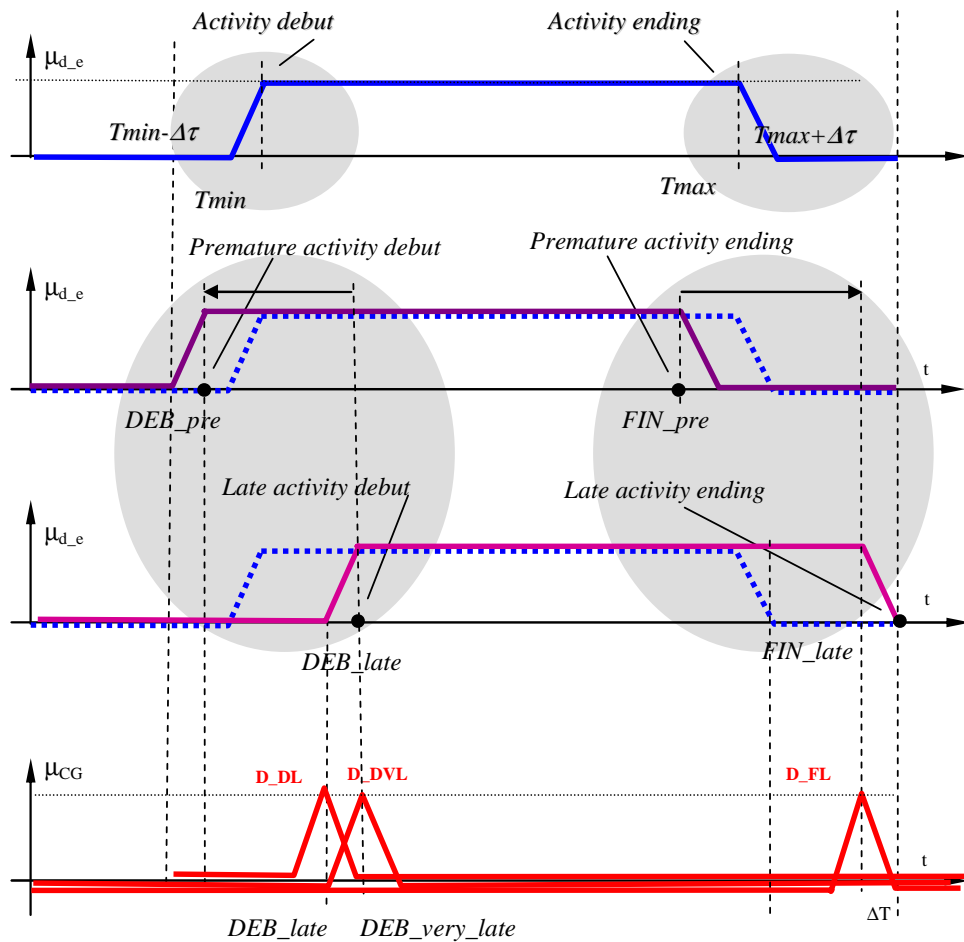
Figure 20. *The fuzzy faults modelling identified at the debut of an activity*

If a tool capable of implementing the critical states prognosis strategy is available, the token will be injected into this analysis tool. The elaborated correction strategy returns the token to the control net, loaded with specific information. Subsequent research has led to the creation/development of a dynamic analysis tool for the information received from direct detection. This analysis will allow the prognosis of critical states which will require a preventive maintenance intervention.
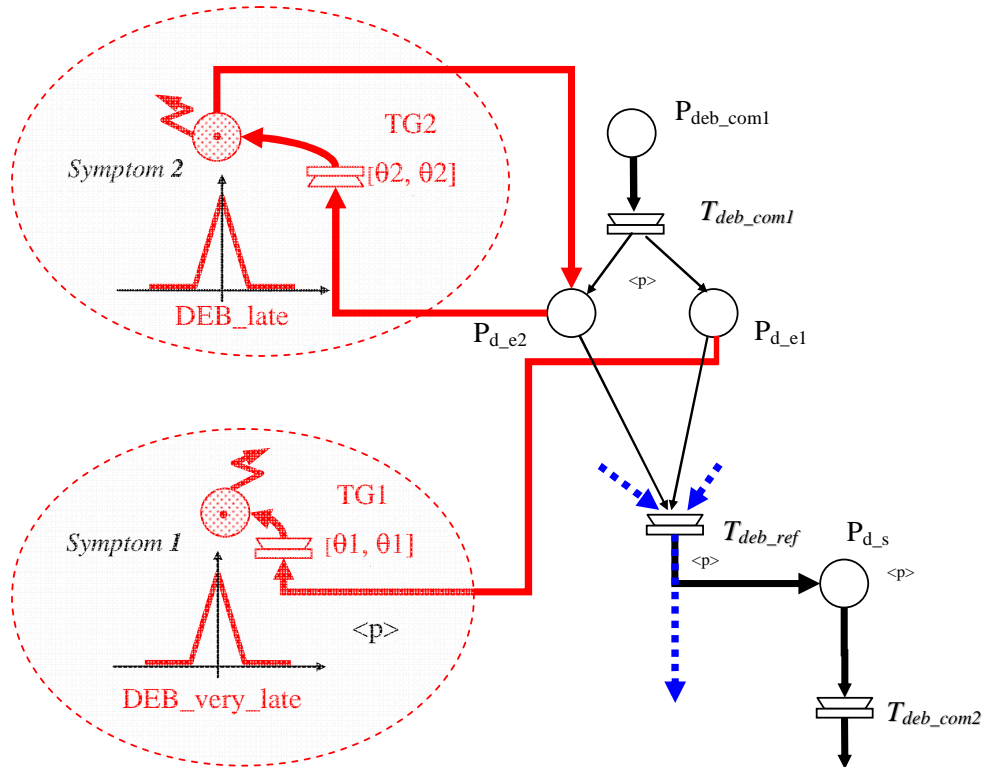
Figure 21. *Refinement of the detection function*

In Figure 22, Symptom 3 translates the very late ending of the monitored activity (D_FL). The token that arrives in A delays here during the execution of the activity. The terminus moment of the delay's ending cannot exceed the date FIN_late of the activity.
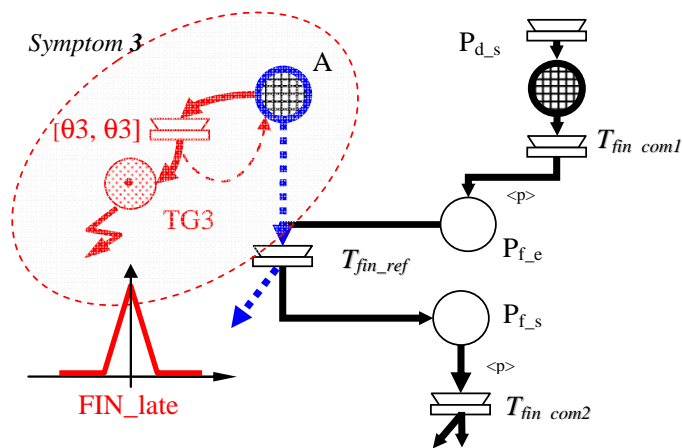
Figure 22. *Detection of a fault occurred during the activity execution*

□ **The fuzzy** modelling **of the detection function**

We will describe the variables associated to the token (the model is OOPN) through fuzzy classes, which will bring extra information to direct detection. We have chosen the variable « time » $\rightarrow$ *t* which is explicit for the temporal transitions. In Figure 23 we have represented the uncertainty of the variable, through its associated membership function, in accordance with the

discourse universe $\left[T_{\min} - \Delta\tau, T_{\min}, T_{\max}, T_{\max} + \Delta\tau\right]$:
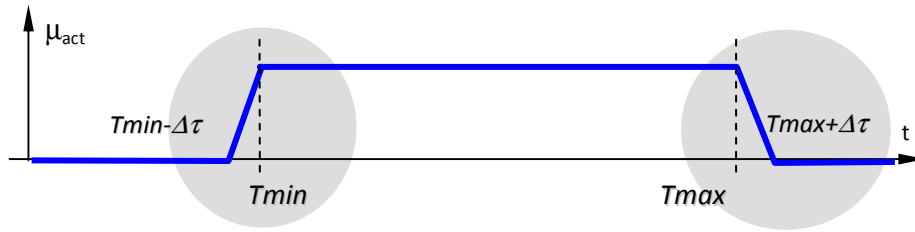
Figure 23. *Fuzzy description of the variable "t"*
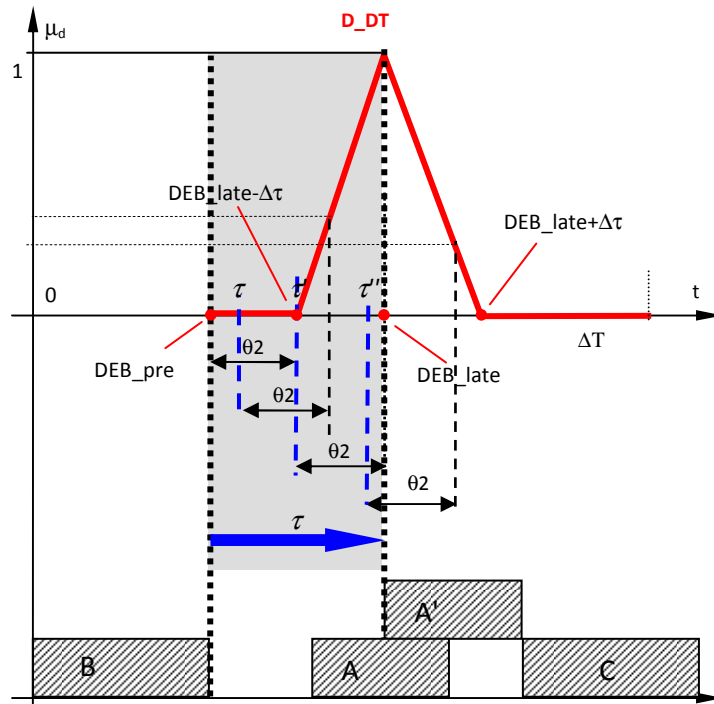
Figure 24. *Fuzzy modelling of an activity's debut moment*

We imagine that the monitored activity is performed during the interval [Tmin, Tmax](Figure 24). In a fuzzy approach, the late debut moment DEB_late is described through a membership function that takes into consideration the variation Δτ of this moment.

We will consider *variable durations* for the sensibilisation of each transition TG: θ1, θ2, θ3. We have marked with τ, τ', τ'' the token's arrival moments in the place of the PN reference model, which is also the input place in TG. After the sensibilisation duration $\theta 2$, the TG2 transition will be fired. The fuzzy description will modify the jetton's attribute – « the fault gravity » with the truth value determined by the membership function.

For the three monitored variables: DEB_late, DEB_very_late and FIN_late, we will project WD mechanisms with sensibilisation values of the TG transitions:

$$\theta_1 = DEB\_very\_late - \Delta\tau + \Delta\tau \cdot \left(e^{-(\tau - DEB\_pre)}\right) - \tau \tag{1}$$

$$\theta_2 = DEB\_late - \Delta\tau + \Delta\tau \cdot \left(e^{-(\tau - DEB\_pre)}\right) - \tau \tag{2}$$

$$\theta_3 = FIN\_late - \Delta\tau + \Delta\tau \cdot \left(e^{-(\tau - DEB\_pre)}\right) - \tau \tag{3}$$

Where τ is the absolute execution moment of transition T_{deb_com1}.

The fault Symptoms occur at the moments:

$$\tau_{Symptom_1} = DEB\_very\_late - \Delta\tau + \Delta\tau \cdot \left(e^{-(\tau - DEB\_pre)}\right) - \tau \tag{4}$$

$$\tau_{Symptom_2} = DEB\_late - \Delta\tau + \Delta\tau \cdot \left(e^{-(\tau - DEB\_pre)}\right) - \tau \tag{5}$$

$$\tau_{Symptom_3} = FIN\_late - \Delta\tau + \Delta\tau \cdot \left(e^{-(\tau - DEB\_pre)}\right) - \tau \tag{6}$$

In Figure 25 we indicate the modelling of firing moments of transitions TG1 and TG2 for an activity that debuts in the interval [5, 15] [thesis Minca E, 2005] :
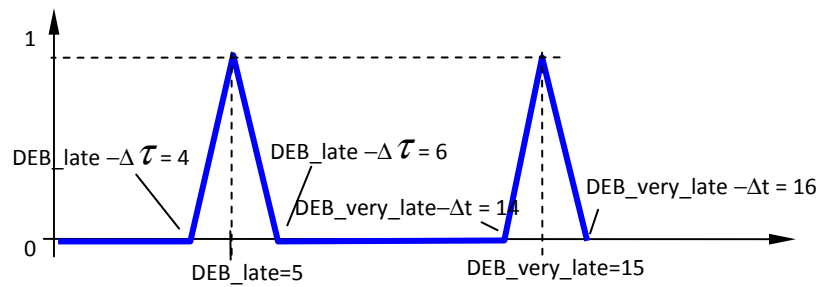
Figure 25. *Fuzzy modelling of moments DEB_late, DEB_very_late*

In Figure 26, Figure 27 we have represented the variable firing moments of transitions TG1 and TG2 according to the firing moment τ of transition T_{deb_com1} : [DEB_late-Δτ], [DEB_late+Δτ], [DEB_very_late-Δτ], [DEB_very_late+Δτ]
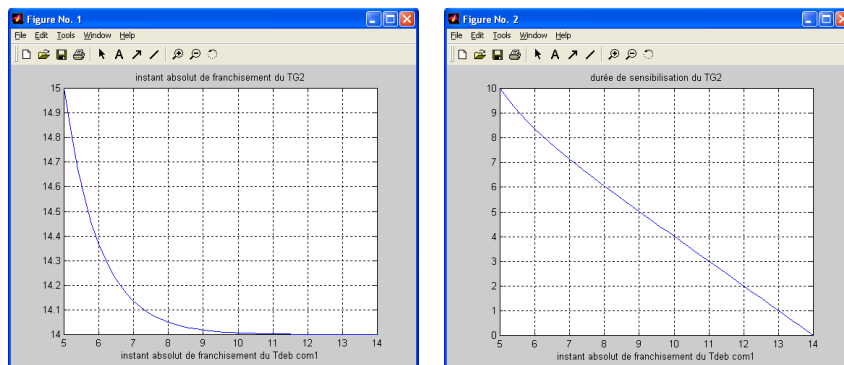
Figure 26. *a) Absolute execution time for TG2 ;*
b) Sensitization duration for TG2
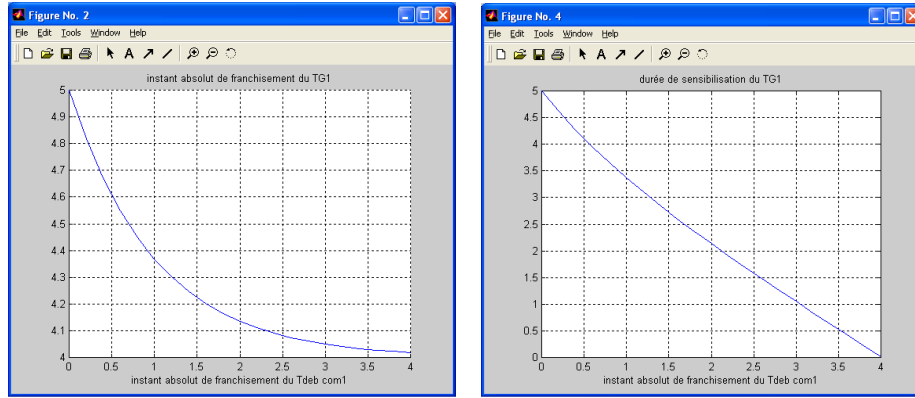
Figure 27. *a) Absolute execution time for TG1 ;*
b) Sensibilisation duration for TG1

When transition T_{deb_com1} is fired at τ, the jetton arrives in positions P_{d_e1} and P_{d_e2} .

If the token delays in P_{d_e2} with $\theta2$ duration, at the moment $\tau+\theta2$ a fault **Symptom 2** will be emitted. This Symptom 2 translates a late ending of the monitored activity. On the contrary, if the token is late in P_{d_e1} up to the moment $\tau+\theta1$, **Symptom 1** will emit a fault signal. The fault gravity is indicated by the fuzzy value determined by the membership function. Eventually, if the token crosses the transition T_{deb_ref} before durations $\theta1, \theta2$, the activity will be faultless.

Mechanisms TG1 and TG2 supervise the correct debut of the monitored activity, in the domain [DEB_pre, DEB_late]. The correct progress of the activity forces the token to delay in P_{de_1} and P_{de_2} with durations that belong to the temporal windows in [FIN_pre, FIN_late].

If its delay in A place exceeds the moment $\tau+\theta3$, then transition TG3 will be fired. Symptom 3 will signal the activity fault that corresponds to the failure of resources in the reference model.

3.4.1. Monitoring Fuzzy Petri Nets. Formal definition

The Monitoring Fuzzy Petri Nets (*MFPN*) tool belongs to the category of PN that model fuzzy logical reasonings. The hypothesis presupposes that there is a fuzzy temporal description for each elementary logical implication. This knowledge allows the determination of truth values for complex logical sentences or phrases that describe the human expert's experience. The model proposed in this paper is based only on elementary logical implications, different from complex logical constructions in papers ([Che, 90], [Loo, 88]).

Compared to Combacau's proposal, the *TOOPN* model does not integrate the advanced monitoring function. This function is implemented with the tool dedicated to dynamic monitoring modelling - *MFPN*. *MFPN* is conceived as a cooperative model in relation to the *TOOPN* model of monitoring/control functions. The interface of models *TOOPN* and *MFPN* is represented through temporal information of the type fuzzy synchronization signals. These signals are injected in *FPN* together with the fuzzy information that quantifies the uncertainty of knowledge, for the abnormal functioning context of the system.

Communication between the system's model (*TOOPN*) and the monitoring function's model *MFPN* is made through synchronization signals-type Symptoms (*labeled "?!" in the MFPN* definition) inspired by Petri Nets with internal synchronizations [Min, 02]. These signals are loaded with extra information offered by the fuzzy formalization of the variable « *fault*

occurrence moment ». At the time when the token arrives in the place that models the fault *Symptom* (WD mechanism), the synchronization signal of *TOOPN* with corresponding transitions from *MFPN* is emitted.

This model is based on predictive information that declare *apriori* certain faults from the faults tree as being critical for the system's evolution. These critical states define the *critical faults path* within FT. The states associated to these critical faults are characterized by threshold values that will initiate correction//recovery actions in critical situations. *MFPN* is based on the temporal prediction of faults that might appear in the monitored system. We propose an analysis tool based either on the logical expression of the faults tree (*fr :* l'Arbre de Défaillances) FT or on a logical rules basis that describe the logical succession of the faults' occurrence, according to the *Analysis of Failure Modes, Effects and Criticity (AFMEC)* (*fr :* l'Analyse des Modes de Défaillances et leurs Effets).

In order to correctly implement the monitoring/maintenance strategy, we conduct an exhaustive description of all normal/abnormal states of the system. In the *MFPN* model, we consider the logical expression that defines the causal chain of faults and their propagation function. We have agreed that these are *basic faults*. We have agreed to name them *derivative faults*. They are logical combinations of basic faults and/or previous derivative faults obtained through logical conjunction and/or disjunction functions by logical variables.

The number of faults $D = \left\{ d_1, d_1, ... d_1, \overline{ds}_{11}, \overline{ds}_{12}, ... \overline{ds}_{jk} \right\} = d \cup \overline{d_s}$

Monitoring Fuzzy Petri Nets (MFPN). Definition.

MFPN is an n-uplet:

$$MFPN = \langle P, T, D, I, O, F, ?!R, \alpha, \beta, \lambda \rangle \tag{7}$$

where:

$P = \{p_1, p_2, ... p_n\}$ the finite number of places that model the system's faults: basic faults and derivative faults. The faults are transient and/or persistent;

$P = \{t_1, t_2, ... t_m\}$ the number of transitions that model the faults' evolution, in accordance with a rule basis that describes their causal dependence. Each transition is associated to a rule;

$D = \{d_1, d_2, ... d_n\}$ the finite number of logical variables associated to basic and derivative faults.

$I : T \rightarrow P$ the entry in places function;

$O : P \rightarrow T$ the entry from places function;

$f_i : T \rightarrow F$ a function that associates each rule to membership functions that describe the truth value of each implication $d_i \rightarrow d_k$, according to time. The time moment corresponds to the direct detection of the fault *Symptom*.

$\alpha_i : P \rightarrow [0,1]$ a function that associates a fuzzy value to the logical variable d_i associated with the place p_i, where $d_i \in D$;

$\beta_j : P \rightarrow D$ a bijective function that corresponds each place p_i, to the logical variable d_i, $d_i \in D$;

$\lambda_k : P \rightarrow [0,1]$ a function that associates the places situated on the critical path, to limit values

λ_k that represent acceptability/permissiveness values for the corresponding fault d_i. λ_k corresponds to a warning threshold for the parameter α. The parameter λ_k is associated to the places that symbolize critical derivative faults;

$?!S = \{s_1, s_2, ..s_i,\}$ the number of fault Symptom-type signals, sent (!) or received (?) by the monitored system. They have the temporal information « occurrence moment τ »;

$!R = \{r_1, r_2, ..r_i,\}$ the number of (fuzzy) signals emitted by the monitoring system in view of initiating the reccovery (the corrective maintenance);

M_0 initial marking corresponding to the basic faults' states.

The *dynamic evolution* of fault propagation was modeled through temporal transitions. Synchronization signals with the model of direct detection *TOOPN* validate the execution of transitions in the assigned temporal windows. Each elementary implication is characterized by the following parameters:

- *The fuzzy value a_j represents the* modelling *of the fault's gravity, according to the moment of its occurrence. This value is elaborated in TOOPN.*

- *The value μ_i represents the truth degreeof the logical implication $d_i \rightarrow d_k$ according to the moment of the signal's occurrence. This value is elaborated in MFPN and represents the membership degree of the fuzzy variable t- a fault signal's emission moment – to the fuzzy description of the implication $d_i \rightarrow d_k$*

- *The moment t of the fuzzy signal's injection represents the moment of crossing the transition MFPN if the transition is not preceded by multiple positions. IIn this case, t represents the possible execution moment of the transition or the debut of its sensitization.*

The characteristics of *MFPN* :

- *MFPN models logical arguments and not resources transformations. For this reason, there is no question of resources production/consumption and no linear logic is respected.*

- *A place may be marked by a token which indicates the true or false value of the logical variable assigned to the position. Since the PN models fuzzy logical arguments, the truth degree of each logical variable is variable. It is expressed by the fuzzy value α associated to the places.*

- *The transition firing does not « consume » the jettons of the positions that belong to the predecessor array, because logical variables maintain their truth degree even after crossing the transition. In this case, each place that belongs to the successor array will be marked according to the simple transition rule, "consuming" copies of the jettons from the predecessor places. This observation describes another mechanism for the simple transition rule.*

- *In conformity with the previous concepts, resources sharing loses its significance. A marked position may be « shared » without a conflict because in each position copies of the effective jettons are consumed.*

The dynamics of fault propagation in MFPN

In the monitored system (modeled with *TOOPN*), the execution moment of the corresponding transition is associated with a fuzzy description by membership functions: FN corresponds to the normal activity in progress and $F(t)$ corresponds to an execution fault's occurrence (Figure 28). Direct detection implanted in *TOOPN* monitors fault occurrence through WD mechanisms. This mechanism will inject a signal *?!s* at the moment of a fault Symptom's occurrence.

Through the fuzzy modelling associated with the signal *?!s* delivery moment, the signal will be associated with a logical credibility value of its production $\mu_i = F(t)$. The function $F(t)$, through the membership functions, describes the truth value of the fault d_j's propagation to the derivative fault d_k. The injected signals are *basic faults*, whereas *derivative faults* are logical combinations of them and/or the derivative ones, as expressed by their causal dependence within FT.
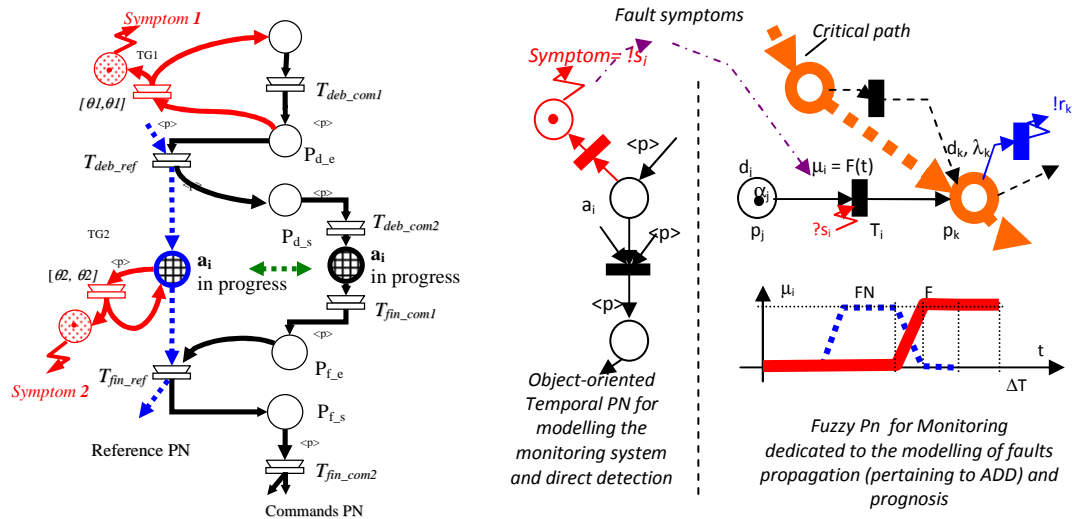
TOOPN model for direct control and detection   Modelling *fault propagation with MFPN*

a)
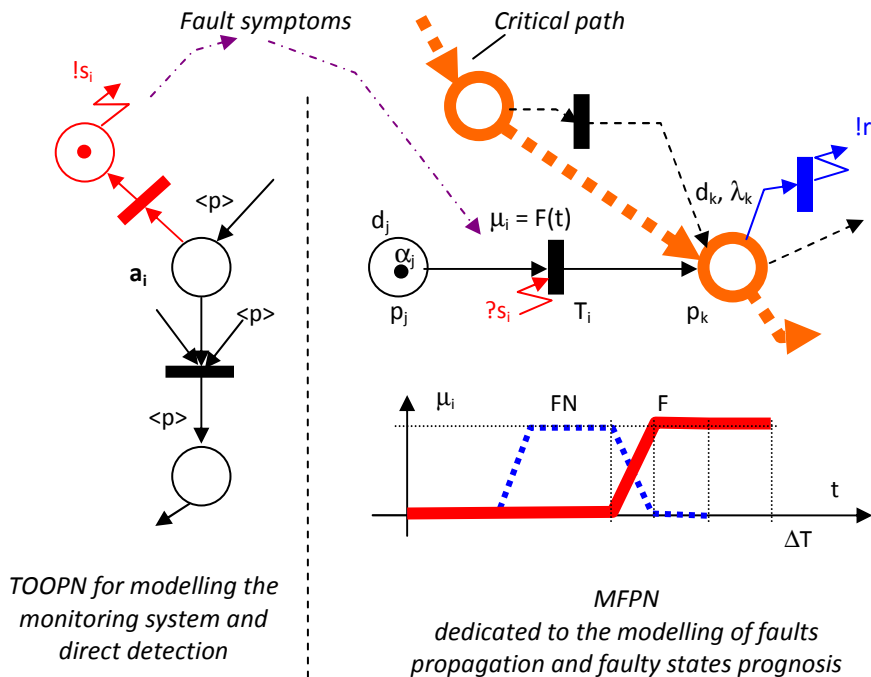
b)

Figure 28. *The modelling of faults propagation a) detailed, b) simplified*

Each transition T_i corresponds to a faults propagation rule modeled through $\mu_i = F(t)$. This function associates each rule with a *dynamic credibility* value. In the *MFPN*, each position corresponds to a fault or a degradation state of the monitored system. Its marking will be associated with a fuzzy value $\alpha_j \in [0,1]$ that represents the fault's « gravity » degree. The logical implication $d_j \rightarrow d_k$ will determine a fuzzy value $\alpha_k \in [0,1]$ corresponding to the derivative fault d_k. This value is calculated based on the generalized modus ponens [Che, 90].

In the proposed approach, the following operators were used:

— $\mathsf{T}(u,v) = \min(u,v)$ - triangular norm (t-norm)
— $\perp(u,v) = \max(u,v)$ - triangular conorm (t-conorm),
— $\mathsf{T}_{\text{probabilistic}}(u,v) = u \cdot v$ - modus ponens operator

The credibility value of the logical implications is calculated as such:

$$\alpha_k = \sup_{t \in \mathsf{T}} \mathsf{T}(\alpha_j, f_R(\alpha_j, \alpha_k)) = \mathsf{T}(\alpha_j, \alpha_k) \tag{8}$$

$$\alpha_j = \alpha_j \cdot s_i \cdot \mu_i = \alpha'_j \cdot \mu_i \tag{9}$$

$$\mu_i = F(t) \tag{10}$$

In **Error! Reference source not found.** and Figure 30**Error! Reference source not found.** we have represented the description by membership functions of the fuzzy variable *t* –fault occurrence moment : in **Error! Reference source not found.** we have represented the membership (by membership functions *F(t)* of the variable t to the class FIN-late of activity a_i. In Figure 30 we have represented the membership of variable *t* to the class DEB_pre of activity a_i.
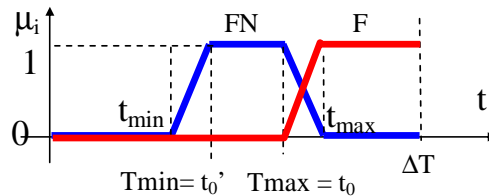
Figure 29. *Membership functions of the variable t to the class FIN_late*
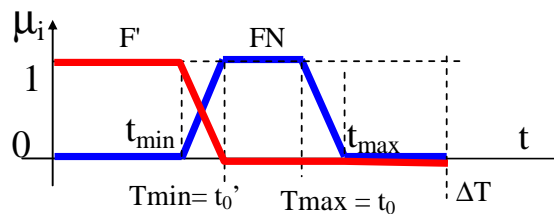
Figure 30. *Membership functions of the variable **t** to the class DEB_pre*

$$FN(t) = \begin{cases} 0 & t < t_{min} \\ (t - t_{min})/(t_{max} - t_0) & t_{min} < t < t_0^{'} \\ 1 & t_0^{'} < t < t_0 \\ (t_0 - t)/(t_{max} - t_0) & t_0 < t < t_{max} \\ 0 & t > t_{max} \end{cases} \tag{11}$$

$$F(t; t_0, t_{max}) = \begin{cases} 0 & t < t_0 \\ (t - t_0)/(t_{max} - t_0) & t_0 \leq t < t_{max} \\ 1 & t > t_{max} \end{cases} \tag{12}$$

Prohibited faults define those faults that lead the system in one of the critical functioning states. If such a fault occurs, an intervention will be performed at the level of the control of activities that cooperated towards its occurrence (Figure 28). These faults define the critical path and are associated with warning thresholds for initiating *maintenance* functions. For this reason, we have introduced for these faults threshold functioning acceptability values in a degraded manner $\lambda : P_{cr} \rightarrow [0,1]$ where P_{cr} represents the number of faults positioned on the critical path.

If a critical fault is marked, and the associated fuzzy value exceeds the threshold value, a fuzzy synchronization signal $!r$ will be sent out. The signal $!r$ will be injected into the corrective maintenance function's model [Min, -b, 03].

3.4.2. Causal relations in the faults tree with MFPN modeling

The FT analysis highlights the logical operators that appear in logical implications. An FT expression expresses logical relations between logical variables, through logical *conjunction* and *disjunction* operators. The usage of the logical operator *negation* is not justified, because we are interested in the faults occurrence, not their absence.

In FT modelling with *MFPN,* we can make the following observations:

- *The set of monitored activities will be identified through criteria that ensue from the corresponding faults' criticality. Even though each activity may become defective, efficiency requires such a selection.*

- *The faults of activities that might enter into a critical state fall within the category of basic faults. They represent the initial marking in the MFPN model.*

- *For each activity that might become defective, the fuzzy description of the variable t - "occurrence moment" will be performed. The membership functions of the variable t to the fuzzy classes F will be defined.*

- *Each fault is identified either by direct detection, or by WD mechanisms that refine direct detection.*

- *MFPN tokens are objects that verify through attributes and methods the restrictions imposed on each transition that can be fired after validation.*

- *The MFPN marking represents an instancing of the modeled system's state (in the case of MFPN – the faults evolution's dynamics). As new faults occur, the places corresponding to the previos faults (the cause of the failure state's occurrence) remain marked (the faults are still persistent). This is a modification of the « simple transition » rule, known in the PN definition. We justify this by the fact that the entire approach is based on the* modelling *of logical rules and not on the* modelling *of the physical resources' production/consumption.*

- *The MFPN transitions are temporal and have predefined sensibilisation intervals in which synchronization signals with TOOPN are expected. In Figure 31, transition*

T_{ij} which models logical implication $d_i \wedge d_j \rightarrow d_k$, may be executed in a temporal window: $\left[t_{0i}, t_{\max\_i}\right] \cap \left[t_{0j}, t_{\max\_j}\right] = \theta_i \cap \theta_j$
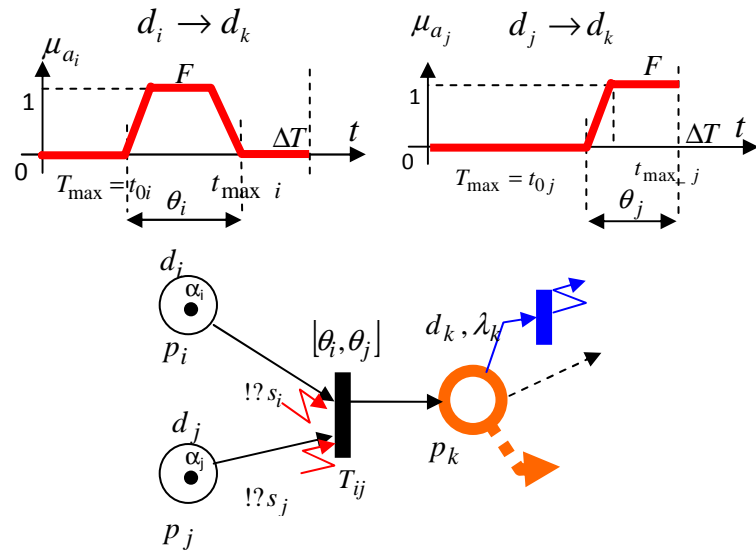
Figure 31. *The modelling of logical implication $d_i \wedge d_j \rightarrow d_k$ in a temporal approach*

3. 5. The algorithm of dynamic monitoring in a fuzzy approach

The usage of *MFPN* imposes the determination of the truth degree for the following logical structures:

Logical rules typologies modeled with MFPN

Conjunction in antecedence:
$$(A \wedge B \rightarrow C) \Leftrightarrow (A \rightarrow C) \vee (B \rightarrow C)$$

Disjunction in antecedence:
$$(A \vee B \rightarrow C) \Leftrightarrow (A \rightarrow C) \wedge (B \rightarrow C)$$

Conjunction in consequence:
$$(A \rightarrow B \wedge C) \Leftrightarrow (A \rightarrow B) \wedge (A \rightarrow C)$$

Disjunction in consequence:
$$(A \rightarrow B \vee C) \Leftrightarrow (A \rightarrow B) \vee (A \rightarrow C)$$
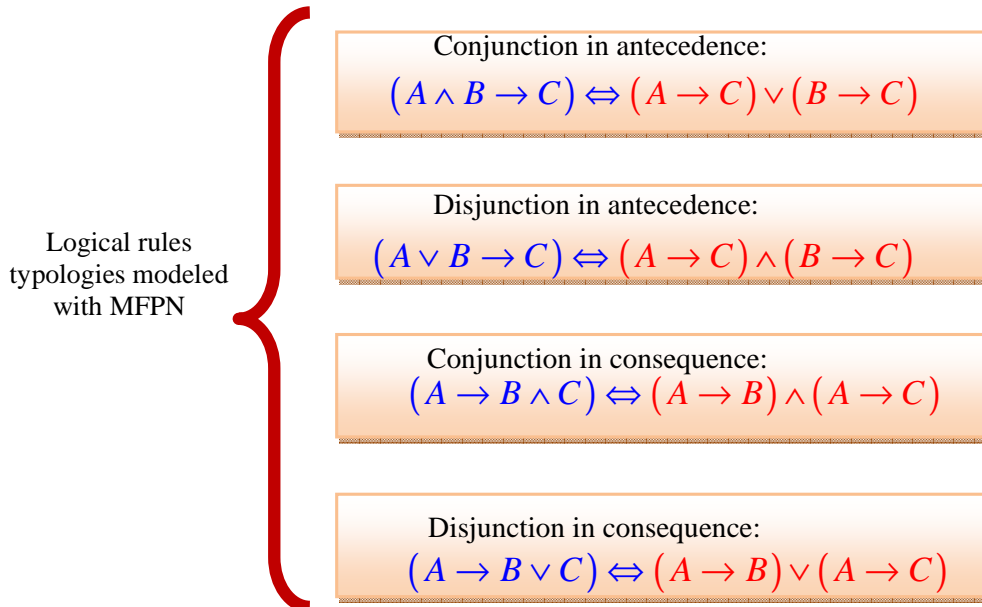
Figure 32. *Elementary logical expressions modeled with MFPN*

- Logical implication: $p \rightarrow q$

— Logical implication with conjunction in antecedence: $p_1 \wedge p_2 .... \wedge p_n \rightarrow q$

— Logical implication with disjunction in antecedence: $p_1 \vee p_2 .... \vee p_n \rightarrow q$

— Logical implication with conjunction in consequence: $p \rightarrow q_1 \wedge q_1 ..... \wedge q_m$

— Logical implication with disjunction in consequence: $p \rightarrow q_1 \vee q_1 ..... \vee q_m$

3.5.1. The dynamics of transitions in the MFPN net

The identification of the *MFPN* model's dynamics, implicitly of the failure states' dynamics, respects the following restrictions:

Sentence 1*: If a Symptom signal $!s_i$ is not received as a synchronization signal, then the transition associated to the elementary implication $d_i \rightarrow d_k$ will never be crossed.*

Sentence 2: *All the mathematical expressions that generalize the fuzzy logic value's calculus, are uniquely applied to the coupled places/transitions that receive synchronization signals*

Sentence 3: *If a transition does not have at least one basic model in its preconditions, it will not receive a synchronization signal. By convention, it is attributed $\mu = 1$*

Sentence 4: *If a transition materializes conjunction in antecedence (Figure 33) $d_i \wedge d_j \rightarrow d_k$, then the fuzzy value of the logical implication is:*

$$\alpha_k = \max(\mu_i, \mu_j) \cdot \min(\alpha_i, \alpha_j) \text{[Min, -a, -b, -c, 03]} \tag{13}$$

Sentence 5: *If a transition models the concurrence of basic and derivative faults $D_i \subset D$ (Figure 34), then the truth value for the logical implication is:*

$$\alpha_k = \mu \cdot \min(\alpha_1, \alpha_2, .. \alpha_m, \overline{\alpha}_{s1}, \overline{\alpha}_{s2}, .. \overline{\alpha}_{sn}) \text{[Min, -a, -b, -c, 03]} \tag{14}$$

$$\mu = \max(\mu_1, \mu_2, .. \mu_m, \mu_{s1}, \mu_{s2}, .. \mu_{sm},) \text{[Min, -a, -b, -c, 03]} \tag{15}$$

Sentence 6: *If a transition models the disjunction of basic and derivative faults $D_i \subset D$ (Figure 35, Figure 34), then the truth value for the logical implication is:*

$$\alpha_k = \mu \cdot \max(\alpha_1, \alpha_2, .. \alpha_m, \overline{\alpha}_{s1}, \overline{\alpha}_{s2}, .. \overline{\alpha}_{sn}) \text{[Min, -a, -b, -c, 03]} \tag{16}$$

$$\mu = \min(\mu_1, \mu_2, .. \mu_m, \mu_{s1}, \mu_{s2}, .. \mu_{sm},) \text{[Min, -a, -b, -c, 03]} \tag{17}$$

Sentence 7: *If a transition models the conjuction in consequence of basic and derivative faults $D_i \subset D$ (Figure 36, Figure 34), then the truth value for the logical implication is:*

$$\alpha_k = \alpha_k \cdot \min(\alpha_1, \alpha_2, .. \alpha_m, \overline{\alpha}_{s1}, \overline{\alpha}_{s2}, .. \overline{\alpha}_{sn}) \text{[Min, -a, -b, -c, 03]} \tag{18}$$

$$\mu = \min(\mu_1, \mu_2, .. \mu_m, \mu_{s1}, \mu_{s2}, .. \mu_{sm},) \text{[Min, -a, -b, -c, 03]}$$

Sentence 8: *If a transition models the disjunction in consequence of basic and derivative faults $D_i \subset D$ (Figure 37) with implications of the form: $d_k \rightarrow d_i$ then the truth value for the logical implications in consequence is:*

$$\alpha_k = \alpha_k \cdot \max(\alpha_1, \alpha_2, .. \alpha_m, \overline{\alpha}_{s1}, \overline{\alpha}_{s2}, .. \overline{\alpha}_{sn}) \text{[Min, -a, -b, -c, 03]} \tag{19}$$
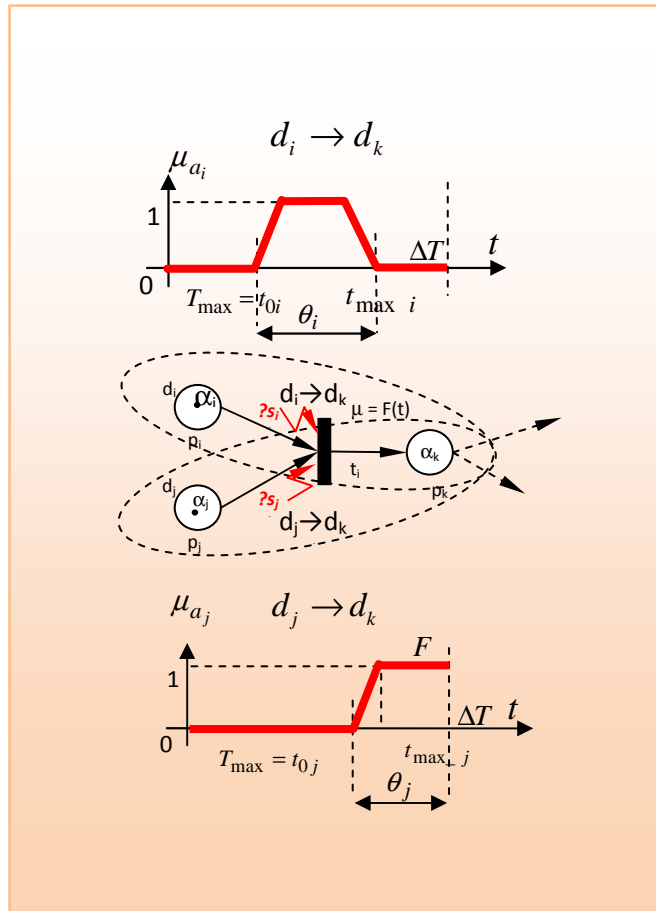
Figure 33. *MFPN modelling* of $d_i \wedge d_j \rightarrow d_k$
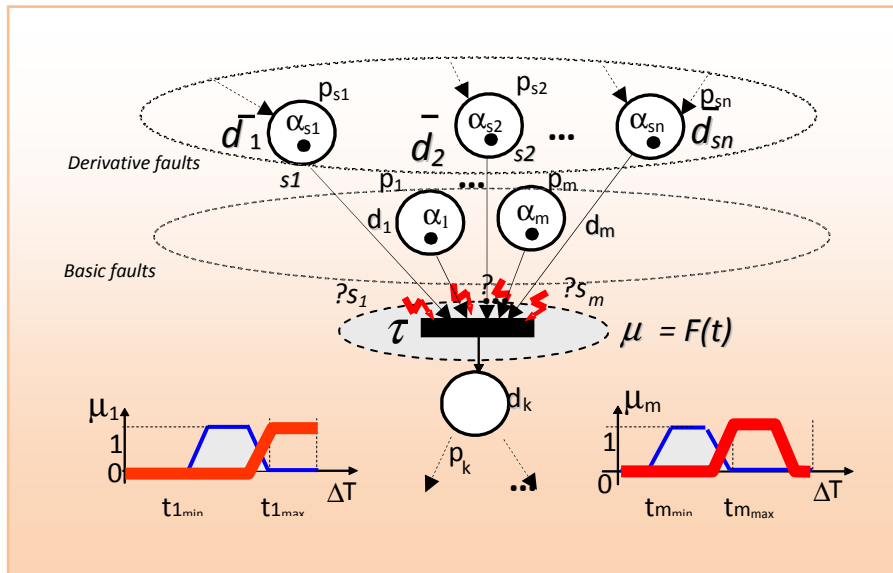
Figure 34. *The modelling of concurrent basic and derivative faults with MFPN*
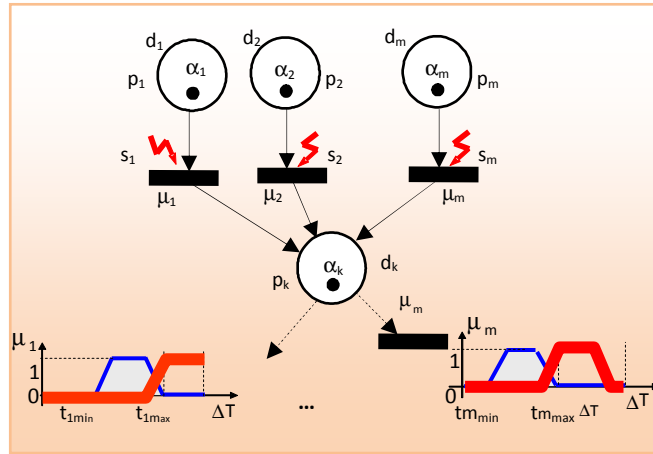
Figure 35. *The modelling with MFPN of the generic number of disjunctive faults in consequence*
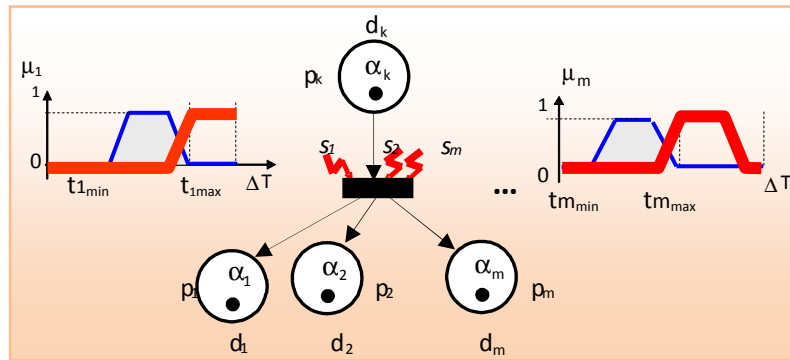
Figure 36. *Modelling the number of disjunctive faults in consequence $D_i \subset D$ by MFPN*
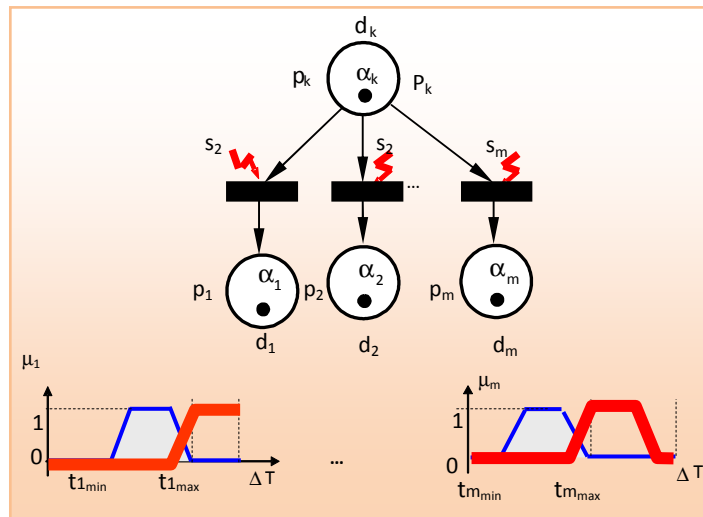
Figure 37. *The modelling of a number of faults with implications: $d_k \rightarrow d_i$*

3.5.2. The algorithm of dynamic detection in MFPN *models*

▬ *The elaboration of the reference model (TOOPN) for the monitored system*

▬ *The implementation of direct detection in the reference model through WD mechanisms.*

▬ *The* modelling *of the temporal aspect of the faults' occurrence moment by defining membership functions for* $\tau_{Simptom}$ *. The fuzzyfication of the variable* $\tau_{Simptom}$ *offers a qualitative aspect to the gravity of the occurred fault. The jetton will acquire as attribute the fuzzy value that quantifies this aspect:*

$$p.gravity\_fault = \mu(Symptom)$$

▬ *Sending synchronization signals* $!s_i$ *towards MFPN model's transitions. By convention, the sent signal is* $!s_i$ *, whereas the received signal is* $?s_i$

▬ *The* modelling *of the faults tree and of the critical path, using the definition possibilities in MFPN. The logical correspondents will be respected: the algebraic sign « + » in FT expresses the variables' disjunction (logical operator SAU), whereas the algebraic sign « * » defines their conjunction (logical operator SI)*

▬ *Elementary implications are related to the corresponding causality faults. The transition associated with the temporal causality is associated with a temporal window* $\left[t_{i_{\min}}, t_{i_{\max}} \right]$ *during which the fault might occur. The fuzzy aspect applied to this event is expressed through the sensitization interval asscociated with extreme values:*

$$t_{\min} = \min_{i=1..k}\left(t_{i_{\min}} \right); \quad t_{\max} = \max_{i=1..k}\left(t_{i_{\max}} \right); \tag{20}$$

▬ *For each transition that models a logical implication, taking into consideration the typologies of logical implications presented in 3.5.1, we will determine :*

  - the credibility degree of the rule: $\mu_i = \mu_a\left(\tau_{Simptom} \right)$

  - the associated fuzzy value that describes the gravity of the fault that is in consequence of the rule (see 3.5.1 and the generalized calculation rules):

$$\alpha_k = \left[\max / \min(\alpha_j, \alpha_i) \right] \cdot \left[\max / \min(\mu_i) \right]; \tag{21}$$

We have presented the necessary stages in the elaboration of *MFPN*, a tool specialized in the temporal analysis of faults propagation. The imposed restrictions (the fuzzy modelling of different variables, the exchange of messages between models with different typologies) are the solution that we propose for the refinement of analysis by integrating the expert's experience and, finally, the refinement of the detection/diagnostic functions.

3. 6. Conclusion

This research highlights an original contribution to the domain of systems monitoring function's formalization and implementation. The tool we propose is of the PN typologie in a fuzzy approach. In the proposed approach, the *MFPN* tool is applied in the modelling of the faults tree and of the faults propagation.

The *MFPN* net is interfaced with the implicit process model with direct detection.

Synchronization signals collaborate two structurally and conceptually different models: *TOOPN* and *MFPN*. Their usage hs bee subsequently applied to other *collaborative PN* typologies. Synchronization signals are « visible » as fault *Symptoms* but can quantify the occurred *fault's gravity*, by the membership functions that describe the linguistic variable *fault occurrence moment*. This information is afterwards propagated and processed by the logical rules basis that ensues from the causal description of faults propagation.

An information return towards the model associated with *corrective maintenance* may be represented by synchronization signals emitted by *MFPN* when the gravity of the faults situated in the *critical path* exceeds the limit values that announce fault *critical states*. The emission of these signals is similar to the reaction loop in automatic systems. The temporal evolution of the fault state gives the proposed tool the dynamic aspect the dynamic aspect of the degraded states' evolution.

Chapter 4

Maintenance platform destined for the control of a flexible fabrication system

The *MFPN* tool was tested on the SORMEL fabrication system (LAB, Besancon, France). The SOMEL system is a flexible fabrication system that contains five workstations and a transportation system with pallet transporter bands, arranged in two circular rings. Each workstation has a robotic system with controllers and cells destined for flexible fabrication (Figure 38). Each station is equipped with pneumatic (pusher, idexor, etc) and electrical (proximity sensors) operating elements. A reading/writing system schedules the fabrication range for the component that is launched in fabrication.

a)   b)
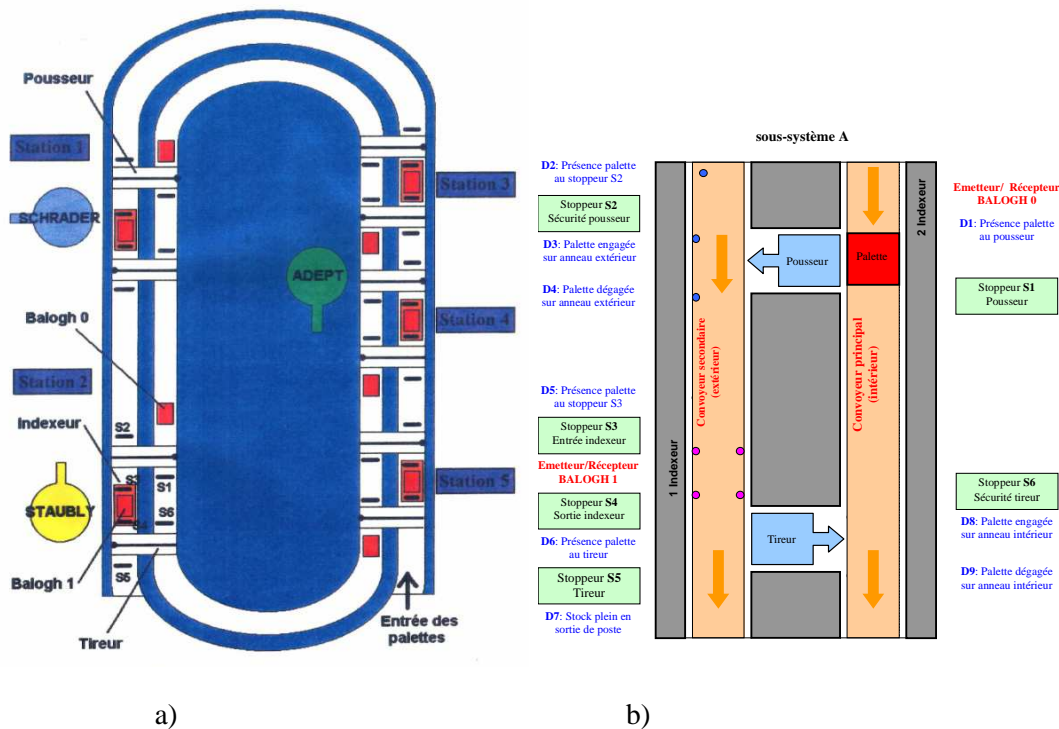
Figure 38. *a) Schematic representation of the SORMEL fabrication system;*
b) Schematic representation of a workstation

The implementation of a fuzzy supervisor required the modelling of dynamics workstations through cooperative *TOOPN* tool (Figure 39): one model for monitoring/control and another destined for the physical system modelling (reference model).

Figure 39. *Dynamic models of workstations by TOOPN*

4. 1. The implementation of detection and diagnostic with MFPN

We propose the modelling of the faults sub-tree for a degraded functioning sequence: « the pallet blocked at the pusher » [Pro, 01]:

$$F = [(a+b+c+d) \cdot e] + b + c \qquad (22)$$

where:

a = 'blocked pusher'
b = 'stopper S1 blocked down'
c = 'sensor D1 breakdown"
d = 'occupied post (D4=1)'
e = 'station destined for reprogramming'

The logical expression of F may be equated in the following rules concepts (Figure 40):

R1: *IF (a OR b OR c OR d) THEN g* $(FC = \mu_{R1})$
R2: *IF (g AND e) THEN f* $(FC = \mu_{R2})$
R3: *IF (f OR b OR c) THEN h* $(FC = \mu_{R3})$

The faults in F were associated with linguistic variables $\{d_1, d_2, d_3, d_3,\}$:

$$F = \left[\underbrace{\left(d1 \cup d2\right) \cap d3}_{ds1}\right] \cup \underbrace{\left(d4 \cap d1\right)}_{ds4} \cup \left[d3 \cap \underbrace{\left(d1 \cup d4\right)}_{ds2}\right]$$

$$\underbrace{}_{ds5} \qquad\qquad \underbrace{}_{ds3}$$

$$\underbrace{}_{ds6}$$

Figure 40. *Representation of causal faults dependence in FT*

The *MFPN* model corresponding to the faults tree FT is:
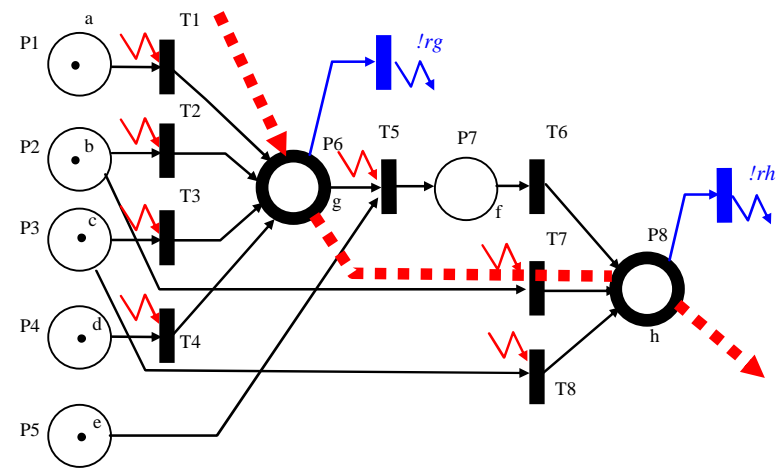
Figure 41. *Modelling F through MFPN*

The occurrence of fault « a » will be accompanied by the emission of a synchronization signal in *MFPN* with *TOOPN* at the level of transition T1. Similarly, the occurrence of fault « b » will be signaled through the signal injection in *MFPN* which will validate transitions T2 and T7.

Positions P3, P4, P5 correspond to faults c, d, and e. The initial marking of net $m0 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \end{bmatrix}^T$ indicates the basic faults that have a maximum occurrence probability.

4. 2. The temporal analysis of faults propagation in the SORMEL system

By applying the algorithm presented in **Error! Reference source not found.**, the following stages will be followed:

a) *The elaboration of the MFPN model in accordance with the faults tree FT (Figure 41) ;*

b) *Identifying basic faults and their derivatives:* $\langle a, b, c, d, e, g, f, h \rangle$;

c) *Identifying threshold faults and values:*
$$\Lambda = \begin{bmatrix} \lambda_g, \lambda_h \end{bmatrix}, \quad \{P_6, P_8\} \in \{critical \quad path\}$$

d) *Determination of initial marking M_0 of MFPN :* $m_O = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \end{bmatrix}^T$

e) *Determination of fuzzy values associated to the logical expressions:* $R = \{R_1, R_2, R_3\}$:

$$R1 = \begin{cases} a \vee b \vee c \vee d \rightarrow g \Leftrightarrow \\ (a \rightarrow g) \wedge (b \rightarrow g) \wedge (c \rightarrow g) \wedge (d \rightarrow g) \\ \mu_{R1} = \min(\mu_{ag}, \mu_{bg}, \mu_{cg}, \mu_{dg}) \end{cases}$$
$$\Rightarrow \quad \alpha_g = \max(\alpha_a, \alpha_b, \alpha_c, \alpha_d) \cdot \mu_{R1}$$

$$R2 = \begin{cases} g \wedge e \rightarrow f \Leftrightarrow \\ (g \rightarrow f) \vee (e \rightarrow f) \\ \mu_{R2} = \max(1, \mu_{ef}) = 1 \end{cases}$$
$$\Rightarrow \quad \alpha_f = \min(\alpha_g, \alpha_e)$$

$$R3 = \begin{cases} f \vee b \vee c \rightarrow h \\ (f \rightarrow h) \wedge (b \rightarrow h) \wedge (c \rightarrow h) \\ \mu_{R3} = \min(1, \mu_{bh}, \mu_{ch}) \end{cases}$$
$$\Rightarrow \quad \alpha_h = \max(\alpha_f, \alpha_b, \alpha_c) \cdot \mu_{R3}$$

f) *Determination of signals vector S and determining vector A with initial fuzzy values of the logical variables associated with places* $P = \{P_1, P_2, \ldots P_8\}$:

$$S = \begin{bmatrix} \min(s1,\ 1) \\ \min(s2,\ 1) \\ \min(s3,\ 1) \\ \min(s4,\ 1) \\ \min((s1 + s2 + s3 + s4) \times s5,\ 1) \\ \min((s1 + s2 + s3 + s4) \times s5,\ 1) \\ \min(s2,\ 1) \\ \min(s3,\ 1) \end{bmatrix} \begin{matrix} \textbf{T1} \\ \textbf{T2} \\ \textbf{T3} \\ \textbf{T4} \\ \textbf{T5} \\ \textbf{T6} \\ \textbf{T7} \\ \textbf{T8} \end{matrix} \; ; \quad A = \begin{bmatrix} \alpha_a \\ \alpha_b \\ \alpha_c \\ \alpha_d \\ \alpha_e \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

g) *Determination of marking M :*

$$Post = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \begin{matrix} \mathbf{P1} \\ \mathbf{P2} \\ \mathbf{P3} \\ \mathbf{P4} \\ \mathbf{P5} \\ \mathbf{P6} \\ \mathbf{P7} \\ \mathbf{P8} \end{matrix}$$

$$m = m0 \oplus (Post \otimes S);$$

$$m = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \oplus \left(\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \otimes \begin{bmatrix} \min(s1,\,1) \\ \min(s2,\,1) \\ \min(s3,\,1) \\ \min(s4,\,1) \\ \min((s1+s2+s3+s4)\times s5,\,1) \\ \min((s1+s2+s3+s4)\times s5,\,1) \\ \min(s2,\,1) \\ \min(s3,\,1) \end{bmatrix} \right)$$

h)   *Determination of the fuzzy values corresponding to each place* $P = \{P_1, P_2, ... P_8\}$:

$$A = \begin{bmatrix} \alpha_a \\ \alpha_b \\ \alpha_c \\ \alpha_d \\ \alpha_e \\ \overline{\alpha_g} \\ \overline{\alpha_f} \\ \overline{\alpha_h} \end{bmatrix} \text{ et } \begin{bmatrix} \alpha_a \\ \alpha_b \\ \alpha_c \\ \alpha_d \\ \alpha_e \\ \overline{\alpha_g} \\ \overline{\alpha_f} \\ \overline{\alpha_h} \end{bmatrix} = \begin{bmatrix} \alpha_a \\ \alpha_b \\ \alpha_c \\ \alpha_d \\ \alpha_e \\ \min(\mu_a, \mu_b, \mu_c, \mu_d) \cdot \max(\alpha_a, \alpha_b, \alpha_c, \alpha_d) \\ 1 \cdot \min(\alpha_e, \overline{\alpha_g}) \\ \min(\mu_b, \mu_c) \cdot \max(\alpha_b, \alpha_c, \overline{\alpha_f}) \end{bmatrix}$$

i)   *Launching the corrective maintenance if fuzzy values* $\overline{\alpha_g}$ *and* $\overline{\alpha_h}$ *exceed the threshold values* λ_g *and* λ_h.

j)   *Defining the RFPN tool destined for corrective maintenance.*

4. 3. The implementation of the corrective maintenance function

Corrective maintenance is similar to the recovery action and is launched through the synchronization signals injection between *MFPN* and *RFPN*. The critical path indicates the faults (associated of *g* and *h* places in Figure 41) which send fuzzy signals towards the fuzzy expert system modeled by *RFPN* (Figure 44).
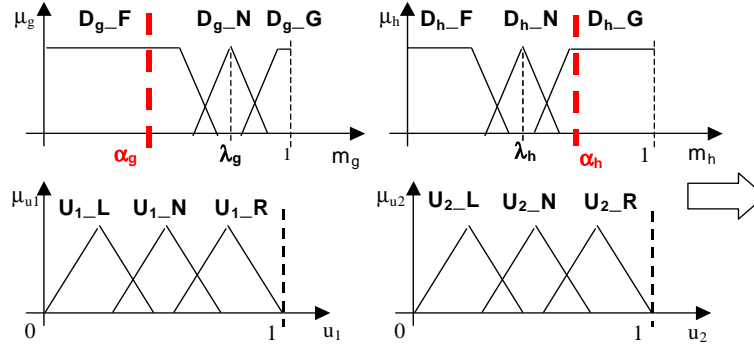
Figure 42. *Fuzzy rules concepts for maintenance*

These fuzzy signals may initiate a corrective maintenance only if all input places in transition t_0, synchronized with the rules concepts $\Re$, have received the signals $!r$ for synchronization with *MFPN*. The output variables u_1 and u_2 represent corrective maintenance commands.

4. 4. Recovery Fuzzy Petri Nets. Formal definition

The Recovery Fuzzy Petri Nets (RFPN) is an n-uplet:

$$RFPN = \left\langle P, T, D, R, X^k, Y^q, \zeta_x, \zeta_y, ?!S, M_0, I, O, f, \lambda \right\rangle \text{ with:}$$

$P = P^k \cup P^q$ the finite number of places: P^k - fuzzy input places, P^q fuzzy output places;

$T = \{t_1, t_2, . t_n\}$ the finite number of transitions set;

$D = D^x \cup D^y$ the finite number of logical variables set. D^x and D^y represent classes of variables, placed in antecedence, respectively in consequence of the fuzzy rules concepts R;

$R = \bigcup\limits_{w=1}^{r} R^w, R^w : D^x \to D^y$ the number of fuzzy logical rules. We imagine that R's rule concepts may be incomplete from the point of view of exhaustive combination possibilities of logical variables associated with D^x respectively D^y;

$X^k = \{X_{11}, X_{21}, ... X_{k1}, .. X_{k2}, , ... X_{km}\}$ the finite number $(m \times k)$ of membership functions, defined in the discourse universe [0,1] corresponding to logical variables D^x. k represents the number of input variables;

$Y^q = \{Y_{11}, Y_{21}, ... Y_{q1}, .. Y_{q2}, , ... Y_{qn}\}$ the finite number $(n \times q)$ of membership functions, defined in the discourse universe [0,1] corresponding to logical variables D^y. q represents the number of output variables;

$\zeta_x : X^k \to D^x$ a function that sets a fuzzy number X_{ij} in a bijective relation with a logical variable D_{ij}^x placed in antecedence of a logical implication;

$\zeta_y : Y^q \rightarrow D^y$ a function that sets a fuzzy number Y_{ij} in a bijective relation with a logical variable D_{ij}^y placed in the antecedence of a logical implication;

$?!S = \{r_1, r_2, ..., r_{k \times q}\}$ the number of maintenance signals ;

$M_0 : P^k \rightarrow \{v_i = \langle 0,0,...0 \rangle\}_{i=1:k}$ the initial marking of input places $p_i \in P_k$;

$I : T \rightarrow P^k, O : T \rightarrow P^q$ states' input/output functions;

$f : P \rightarrow \bigcup\limits_{w=1}^{k \times q} F^w$ a function that associates each place $p_i \in P_k$ with membership functions corresponding to the fuzzy description F^w of its marking;

$l : P_k \rightarrow [0,1]$ a function that associates each place $p_i \in P_k$ with a threshold value l_i of acceptability/permissiveness of the corresponding fault, from the point of view of maintenance actions. l_i corresponds to a warning threshold and P^k represents the number of places corresponding to critical places established through direct detection.
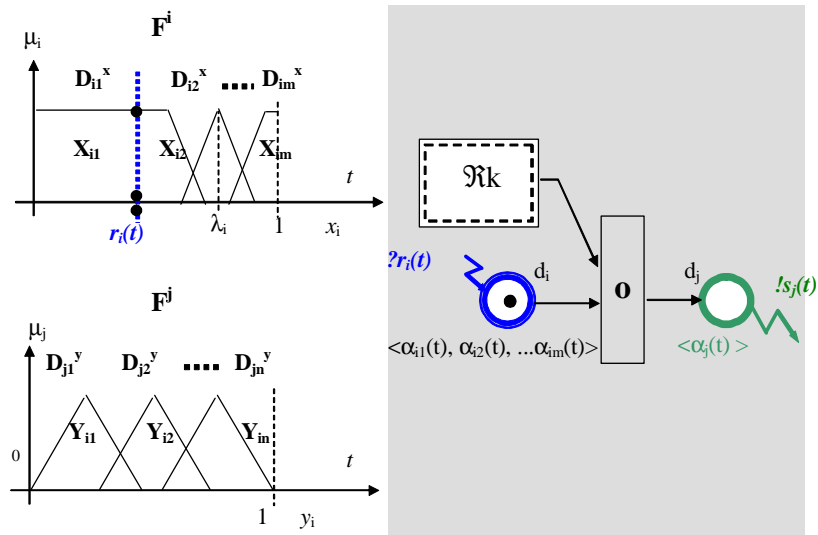
Figure 43. *The maintenance function modelling with RFPN*

The maintenance mechanism modeled with *RFPN* implements a fuzzy logical rules basis (Figure 44) :

$$\Re \begin{cases} if \quad D_{g\_}N \quad si \quad D_{k\_}N \quad atunci \quad U_1\_N \quad si \quad U_2\_L \\ if \quad D_{g\_}G \quad si \quad D_{k\_}N \quad atunci \quad U_1\_R \quad\quad U_2\_R \\ if \quad D_{g\_}N \quad si \quad D_{k\_}G \quad atunci \quad U_1\_L \quad\quad U_2\_R \end{cases}$$ where:

F → "weak"
N → "normal"
G → "grave"
R → "fast"

L → "slow"
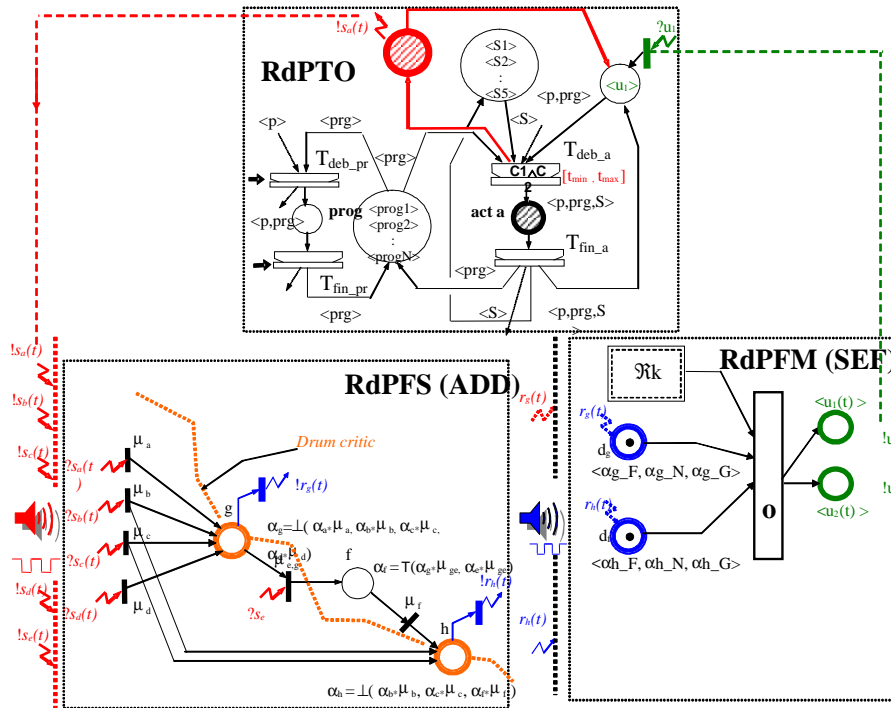
Figure 44. *Modelling the real-time monitoring-control system (FT = faults tree, FXS = fuzzy expert system*

4. 5. The software platform dedicated to fuzzy monitoring by MFPN

The innovation of the theoretical research so far is the modelling tools: *MFPN* and *RFPN*, set in a collaboration relation with *TOOPN* by fuzzy synchronization signals. The entire approach was implemented in a client-server software platform destined for the analysis/decision and finally for the corrective maintenance engineering of the SORMEL fabrication system (LAB Besancon, France) (Figure 46).

The fault signals emitted by the reference model are acquired through real-time acquisition functions. The software product was tested on different degraded functioning states scenarios. Random values were attributed to fuzzy variables α_a, α_b, α_c, α_d, α_e according to the fault occurrence possibility. The experiment for which we show the measured results corresponds to the occurrence of fault b= 'stopper S1 blocked down'. For faults situated on the critical path, variable threshold values were established, according to the critical context created by the operator (Figure 45)
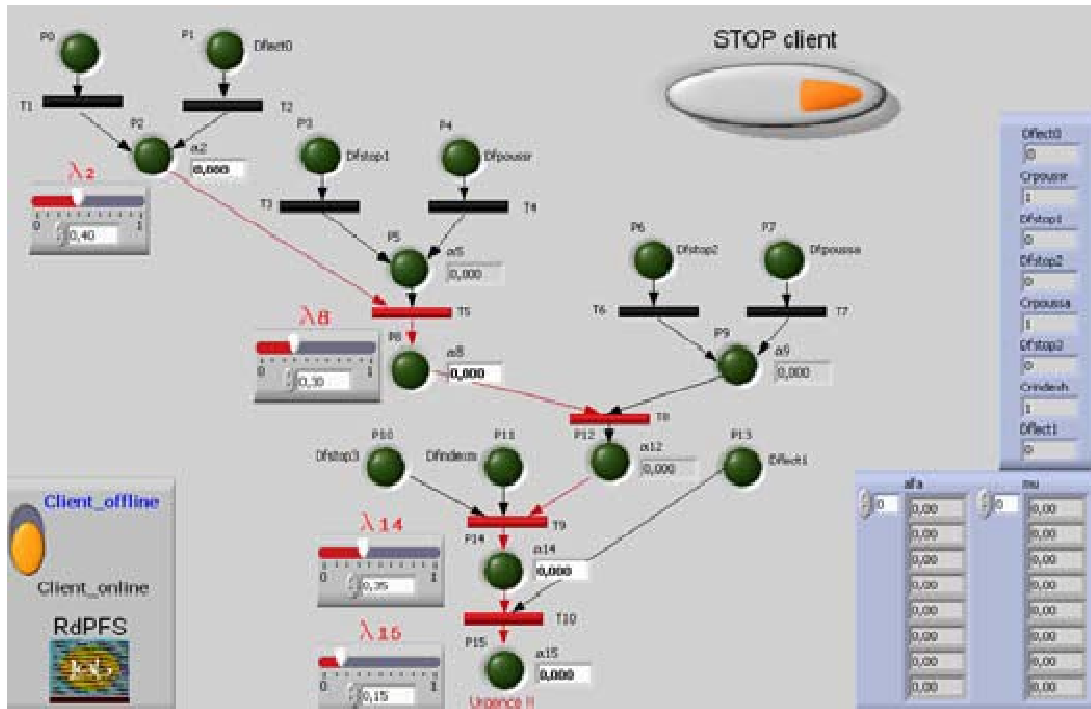
Figure 45. *Client application destined for faults monitoring of an FT under the platform Labview*
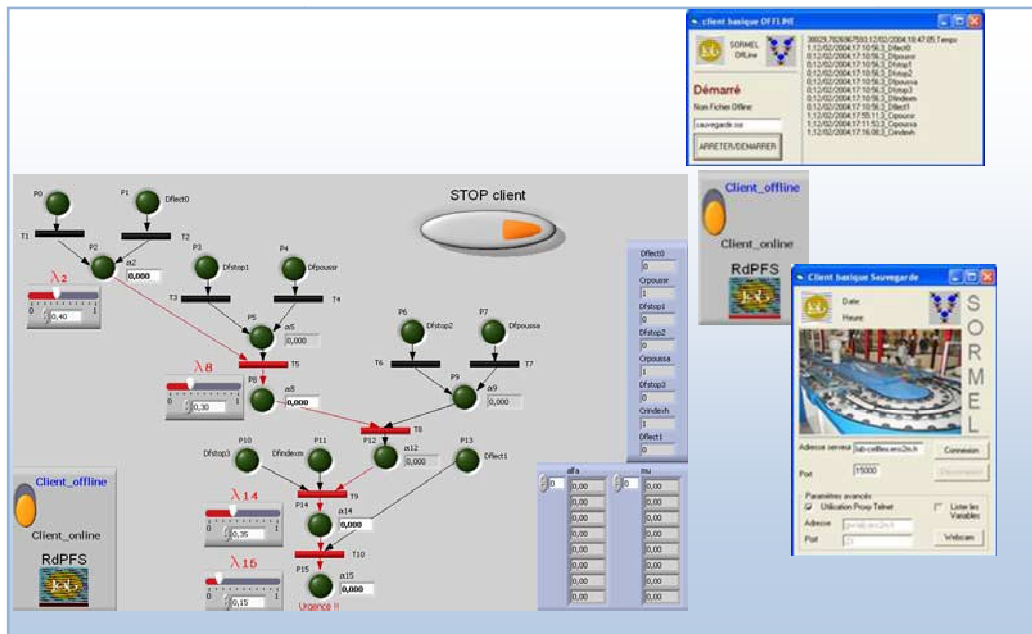
Figure 46. *Client-server monitoring system destined for dynamic monitoring/control of the SORMEL fabrication system*

In Figure 47 a), b) we present the fuzzy description by membership functions of faults *g* and *h*. Similarly, in order to model the rules set $\Re$, we have performed the cartesian product of variables involved in the antecedence and consequence of each rule (Figure 48), followed by their intersection (Figure 49). In the end, we have obtained the fuzzy representation of the rules

set $\Re$ (Figure 50), generated by their intersections in Figure 49.

a)   b)   c)
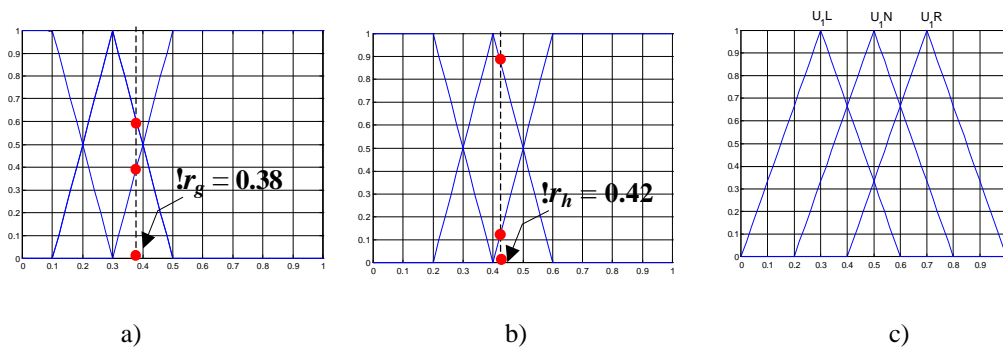
Figure 47. *Membership functions of variables g,h, and u₁ to fuzzy classes*

a)   b)
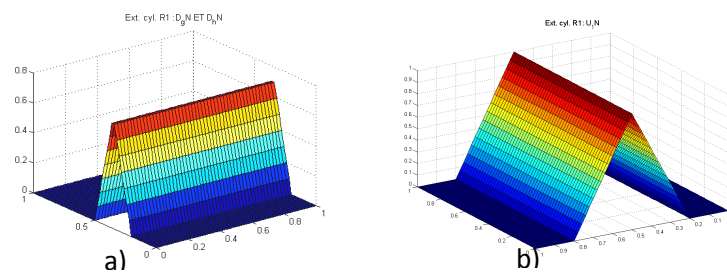
Figure 48. *a) Cylindrical extension of the intersection (D_g_N ET D_h_N) ; b) Cylindrical extension of $U_1\_$ N*
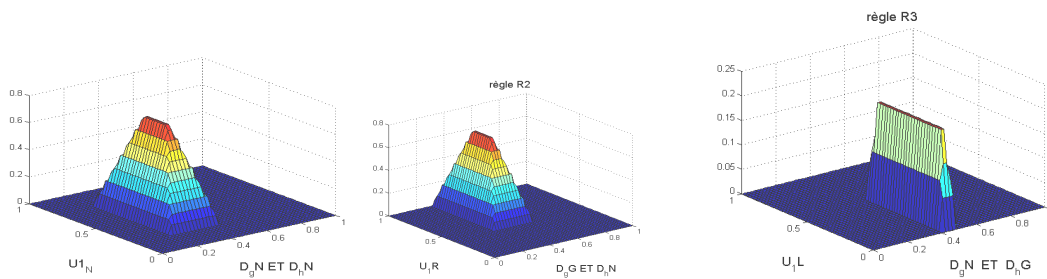
Figure 49. *Representation of fuzzy rules R1, R2, R3*

The rules set $\Re$ corresponds to the aggregation of rules: $\Re_1$, $\Re_2$, $\Re_3$ (Figure 50) :
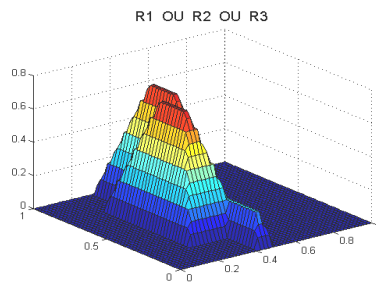
Figure 50. *Representation of fuzzy rules set R*

a)   b)
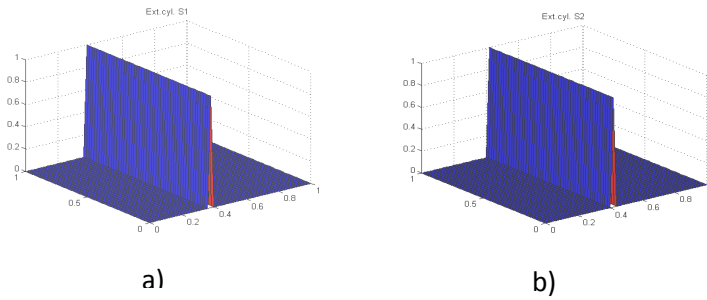
Figure 51. *a) Cylindrical extension of signal s1 ; b) Cylindrical extension of signal s2*

a)   b)
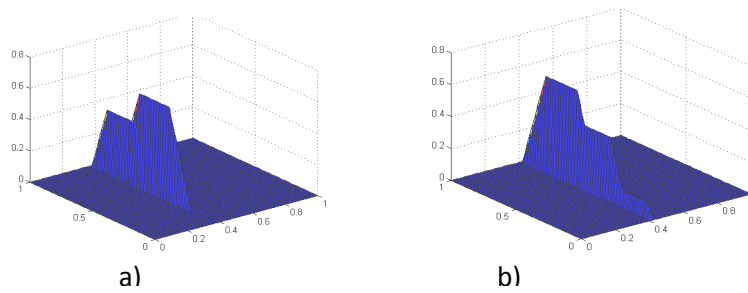
Figure 52. *a) Inference (s1,R); b) Inference (s2,R)*
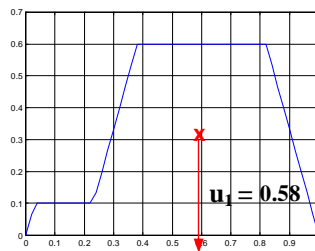
Figure 53. *Defuzzyfication of fuzzy variable U1*

The aggregation of rules is followed by their inference with the input variables: signals $!r_g = s_1$ and $!r_h = s_2$, whose cylindrical extension is presented in Figure 51. The result of the inference mechanism of the rules set $\Re$ with signals $!r_g = s_1$ and $!r_h = s_2$, followed by defuzzyfication, is indicated in Figure 53. The obtained variable U_1 represents the control function transmitted to the corrective maintenance system by the control system.

Chapter 5

Recurrent Synchronized Fuzzy Petri Nets

5. 1. Current Stage

Recurrent Synchronized Fuzzy Petri Nets(*RecSinFPN*) represent an extension of the *MFPN* proposal presented in the previous chapter. The recurrent aspect adds an additional precision to the model, namely to the monitoring function if the tool is applied in its modeling. *RecSinFPN* are an extended proposal for distributed systems modeling. The hierarchical structure of a distributed system may describe causal interdependences. Just as well, such a structure may be generated if we want to refine a certain function from a certain point of view. In the case of detection and diagnostic, the *RecSinFPN* tool is used in precisely determining the location of a faulty state, while specifying its occurrence probability. The recurrent aspect of *RecSinFPN* is reflected in the model's possibility to evolve on hierarchical levels, while maintaining at each commutation the state information from the previous level.

Modelling of the recurrent functions usually generates a hierarchical systems structure, in which, when switching from one level to another (from the above hierarchical level), the whole context of the previous context is inherited. From this point of view, the recurrent modelling of the monitored functions impose to refined models with important results concerning the informational context of occurrence the fault states. If this approach is combined with fuzzy descriptions of the identified fault's temporal aspect, specific consistent information is attained.

Uncertain knowledge associated to the discrete events systems monitoring requires specific reasoning and modelling methods adapted to a logic different from the traditional one [Bos, 04], [Car, 93], [Car, 95], [Che, 00]. For many years, hierarchical systems [Fil, 08] have been a practical solution to approaching complex, large –scale systems. Among modelling tools, Fuzzy Petri Nets are the most appropriate for discrete events description using a fuzzy knowledge base. A complete state of the art of the various Fuzzy Petri Net (*FPN*) approaches was published by Cardoso [Car, 95].

The various types of logics (traditional, linear and fuzzy), used in the description of the systems, generate two main categories of *FPN* models: the first class of models is represented by the Fuzzy Expert Systems (*FES*). In this case, FPN is interfaced with the supervised system by information arrived from sensors and represents the equivalent of a fuzzy controller for a discrete events system [Drg, 08], [Zip, 08], [Drg, 07]. Another class of applications modeled by the *FPN* is that which express the inaccuracy of the fuzzy knowledge [Bos, 04], [Loo, 88]. This last type of *FPN* models a physical system by applying linear logic [3] to the resource transformation level. Generally, FPN use traditional logic [Che,00], [Min,-a, 02] at the level of

the sentences semantics.

The modelling of the monitoring discrete events system can be made through various Petri Nets types (ordinary PN, high level PN). We consider the assumption that the possible faults are known a priori and are modeled by specific mechanisms (for example by "*the watchdog*"). To model the monitoring function, an extension of *MFPN* and *TPN* (Temporal Petri Nets) [Min, -b, 02], [Min, -a, 02], [Rac, 03] is used. This integrates the momentary temporal aspect of the failure occurrence, in the supervised system. The Supervised Fuzzy Petri Net *MFPN* [Min, -a, 02], [Rac, 03] is dedicated to the supervisor function model, by integrating the fuzzy logical rule basis that ensues from the logical expression faults tree (FT- fault tree). The SFPN tool models the reunion or the intersection of the logical reasoning, respecting the specific concepts of fuzzy logic.

The *MFPN* tool models the reunion or the intersection of the logical reasoning, respecting the specific concepts of fuzzy logic [Bou, 94], [Dub, 89]. The analysis offers refined information at the level of each fault, transferring signals from the temporary synchronized faults. *MFPN* highlights the characteristics of certain points which materialize the critical path in the strategy of the prediction function.

We propose the *Recurrent Synchronized Fuzzy Petri Net* tool (*RecSinFPN*), which describes the operational mode of the non autonomous systems with hierarchical structure. Its evolution is conditioned by certain external events and by time. The proposed tool can quantify the external faulty context through the receptive transitions for the external events. At the same time, through the fuzzy approach, it refines the external information considering the iterative temporal window where the event is expected to occur. These proposals improve the previous approach [Min, -a, 09], [Min, -b, 09], [Min, -c, 09] of the same tool.

5. 2. Recurrent Synchronized Fuzzy Petri Nets dedicated to detection/diagnostic functions

We propose a Fuzzy Petri Net typology inspired by the work of Chen in [Min, -b, 02], and adapted to the supervision functions modeling. Chen's model is dedicated to the static logical rules model. This approach is not entirely satisfactory for ~~the~~ dynamic monitoring. For this reason, we propose the Recurrent Synchronized Fuzzy Petri Nets as an extension of the *MFPN*. In order to refine the detection/diagnostic model, we define a fuzzy model able to integrate the events' moment of occurrence, in an iterative way.

In this direction, the Recurrent Synchronized Fuzzy Petri Nets (*RecSinFPN*) are an extension of these models. In order to model detection/diagnostic functions, we define a fuzzy model able to refine the instants of events occurrence. The *RecSinFPN* model is efficient if the specific hierarchical function is used to create recurrent behavior. Thus, the model must respect the following features:

> - *synchronized relations with the external events, which means that certain transitions of the model are associated and fired by the external events (faults)*
>
> - *repeated inspection of the occurring events. This can be achieved by the hierarchical structure that aims at repeating the detection function in different temporal windows, associated to each hierarchical level.*
>
> - *the implementation of the recurrent aspect of the detection action. Based on the result obtained on each horizontal level of the hierarchy, the system shall continue to evolve hierarchically downwards, in the node that corresponds to the result obtained*

on the previous level.

- with each switch to another hierarchical level, the system iteratively executes the detection function, attempting to synchronize with the external event associated to the transactions, in temporary windows which are progressively increased.

5. 3. Tool definition

Recurrent Synchronized Fuzzy Petri Nets (*RecSinFPN*) (Figure 54)are defined as a n-uplet:

$$RECSinFPN = \langle SinFPN, m, n \rangle \tag{23}$$

where:

SinFPN   *Synchronized Fuzzy Petri Net (for the recurrent system approach, SinFPN is called "Elementary SinFPN"*

m   *hierarchical levels in the elementary SinFPN network*

n   *hierarchical levels in the elementary hierarchical RecSinFPN network*

$$SinFPN = \langle P, P^*, T, E, I, O, F, Sinc, f, D, M_0 \rangle \tag{24}$$

where:

$P = \{p_1, p_2, .. p_n\}$ *set of places ;*

$P^* = \{P_1^*, P_2^* ... P_m^*\}$ *object-oriented set of places;*

$T = \{t_1, t_2, .. t_n\}$ *set of transitions;*

$E = \{E_1, E_2, .. E_n\}$ *set of external events;*

$I : T \rightarrow P$ *place's input function ;*

$O : P \rightarrow T$ *place's output function ;*

$F(t) : T \rightarrow [0,1]$ *associative function that establishes a credibility value $\mu = F(t)$ that is the time variable for each transition $t_i \in T$. μ represents the truth degree of the sentence corresponding to the transition. The moment t corresponds to the instant $t \in d$ when the external event E_i will be received by the modeled system;*

$Sinc : T \rightarrow E \cup e$ *set of transitions with values on the set of events E united with the e event which is permanent. If a transition has not an external event E associated, it is considered that it is associated with the event e = event with permanent occurrence;*

$f : n \rightarrow \Delta T_n$ *a function that associates a temporal window, in which the external event is expected, to every hierarchical level of the elementary SinFPN network;*

$D = \{d_1, d_2, .. d_i\}$ *set of logical variables associated to the P places of the elementary SinFPN network. These variables correspond to the faults that can appear in the monitored system. They contribute to the definition of the successive degradation states of the system. The causality relationship between these variables also determines the m hierarchical levels of the SinFPN structure;*

M_0 *initial marking of the network;*
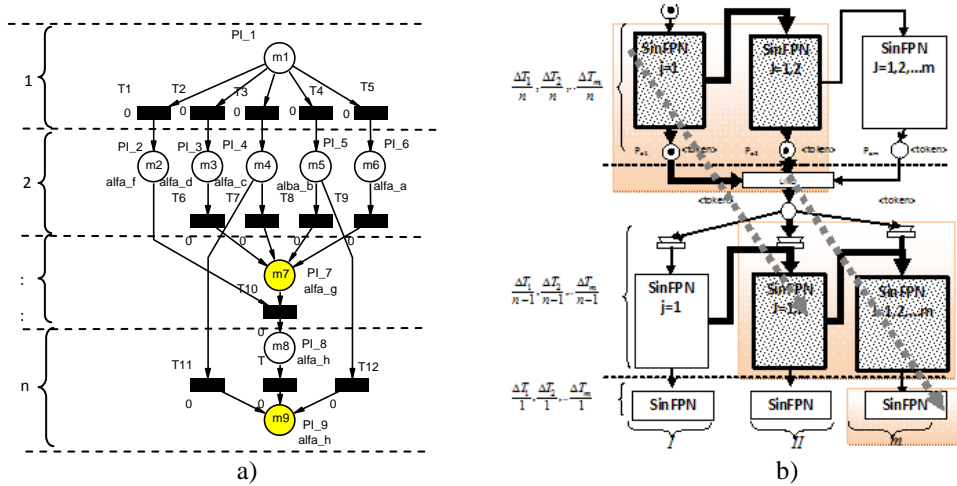
Figure 54. *A)Elementary SinFPN. B) Structure of RecSinFPN*

Classically, in *SinFPN,* when a transition is validated, it can be fired if the event associated with *Sinc* is received. It is supposed that the supervised system is modeled by a temporal PN. In this model – named reference model, the direct detection functions are implemented. The faults occurrence is "visible" in the reference model through "watchdog" mechanisms. In this way, the failure signals are sent into *SinFPN* by the synchronization signals.
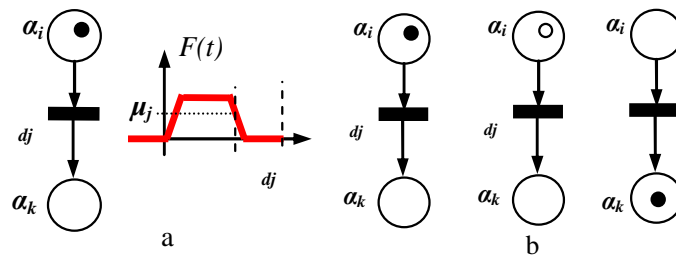
Figure 55. *Marking evolution in the SinFPN*
a) initial marking b) network marking with temporal window d_i

This signal is expected by the associated transition, within the temporal duration window d_i (Figure 55.a). For the interval d_i associated to transition T_j, the token has the reserved status (Figure 56 b). It is the T-timing aspect for the *SinFPN* model. At the moment when faults occurs, the transition is fired and the token takes the value $\mu_j = F(t)$. This value represents the credibility degree associated to the logical rule: " p_i true " or "the fault occurs". The token which arrives to the following place will be loaded with the fuzzy value $\alpha_k = \alpha_i \cdot \mu_j$ (Figure 55.b).

5. 4. Operating mode for logical rules modelling with SinFPN

The *SinFPN* tool is adapted for the modelling of the logical rules, as well as for the modelling of the production resources. In both cases, the network has different operating rules. Various

structures of Petri Nets are possible for modelling (Figure 56.a, b, c).

a)   b)

c)
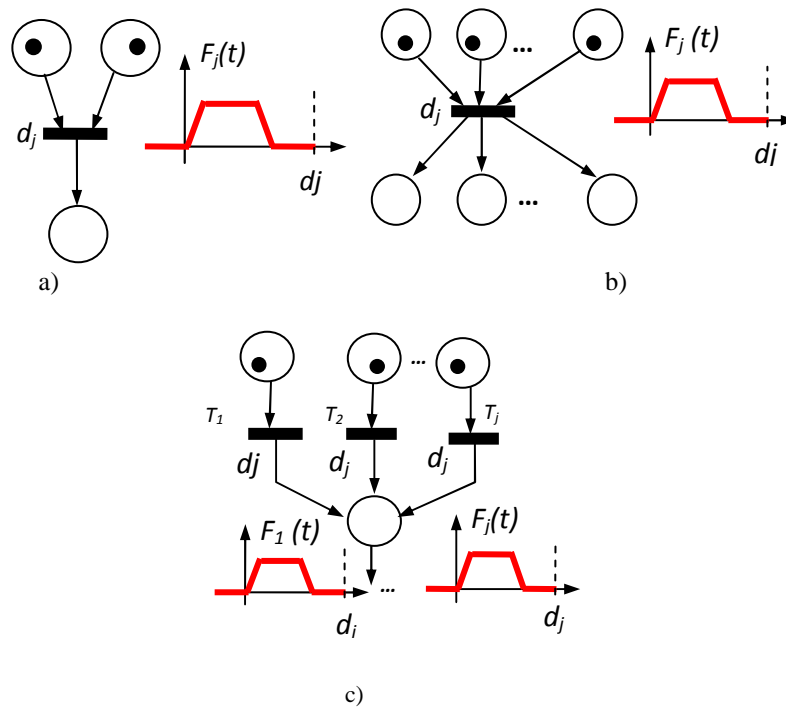
Figure 56. *a) Modelling of the logical rule* $p_1 \wedge p_2 \rightarrow p_k$;

b) Modelling of the logical rule $p_1 \wedge p_2.. \wedge p_i \rightarrow p_{1'} \wedge p_{2'}.. \wedge p_{k'}$;

c) *Modelling of the logical rule* $(p_1 \rightarrow p_k) \vee (p_2 \rightarrow p_k)... \vee (p_i \rightarrow p_k)$

This specialized network *SinFPN* has been proposed in approaches [Min, -a, 09], [Min, -b, 09], [Min, -c, 09]. It is a general modelling tool dedicated to non-autonomous systems with the integration of fuzzy logic. These tools incorporate in theirs structure a set of external events and functions associated with transitions that determine the degree of credibility.

Each transition corresponds to a fuzzy rule and is associated to a function $\mu_j = F(t)$ which describes the possible moment of firing. The function represents the membership function of the fuzzy variable *t* to the fuzzy set defined by the linguistic variable " occurrence of event Ei ". Being variable in time, the value of credibility μ of the rule modeled by the transition associates to each rule a dynamic credibility character. The interval [0 d_j] represents the entire analyzed period and, at the same time, the temporization interval associated to the transitions.

Even if the event occurs in the temporal window $[0, d_j]$, the transition firing will be done after the duration d_j. During the interval $[0, d_j]$, the token of the place p_i represents the reserved token in the place, thus it is not available for firing any other transition.

In our approach, the following operators are considered:

— $T(u,v) = \min(u,v)$ - triangulaire norms (t-norme)
— $\perp(u,v) = \max(u,v)$ - triangulaire conorms (t-conorme)
— $T_{probabiliste}(u, v) = u \cdot v$ - generalized modus ponens operator

For the structures presented in Figure 56, the evolution of the marking is natural, but the fuzzy values associated to the tokens of the following places are determined according to these definitions: c)

$$\text{Figure 56Figure 56.a)} \rightarrow \alpha_k = \min(\alpha_1..\alpha_i) \cdot \mu_j \tag{25}$$

$$\text{Figure 56.b)} \rightarrow \alpha_1 = \alpha_2 = \alpha_k = \min(\alpha_1..\alpha_i) \cdot \mu_j \tag{26}$$

$$\text{Figure 56.c)} \rightarrow \alpha_k = \max\left(\alpha_1\mu_1, \alpha_2\mu_2,..\alpha_j\mu_j\right) \tag{27}$$

5. 5. Operating mode for production systems resources modelling with SinFPN

In this case, the temporizations are different for each transition and are in correspondence with the manufacturing operations durations. For the case in Figure 56 c, we propose a very different evolution of the marking, if the resources of a production system are modeled. After the transition firing, each token will be associated with the fuzzy value $\alpha_k = \alpha_i \cdot \mu_j$.

Each token will independently have the status of reserved token during the interval $[0\ d_j]$ associated to each transition (Figure 57). Otherwise, in the case of Fig. 2. a, b, we preserve the same calculation method for the token's fuzzy values, which is completed after the corresponding transition is fired.

To optimally exploit this tool, we present the basic principles of the evolution analysis for each network. For this, we will focus our study on the transitions, and more precisely on the transitions with concurrent places.

a)   b)
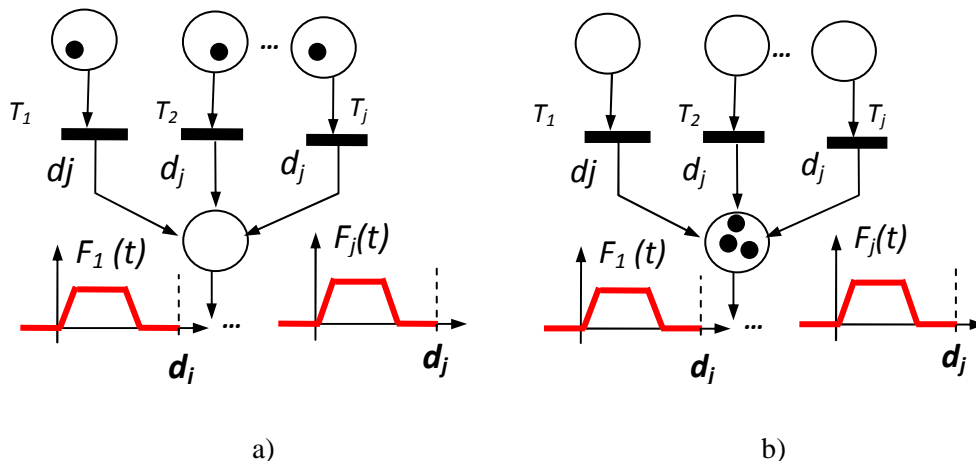
Figure 57. *a) SinFPN for production systems resources modelling*
b) states system after the firing of transitions

Sentence 1:   *If a transition has not an external event E associated to it, we consider that it has the event e = event with permanent occurrence associated to it. The associated function will be the constant function F(t) =1*

Sentence 2:   *If a transition has not a duration of temporization d associated to it, we consider that its duration is null, thus the marking after firing will be an unstable marking.*

Sentence 3   *If the following logical rule is modeled $d_1 \wedge d_2 .. \wedge d_i \rightarrow d_k$ or $(d_1 \rightarrow d_k) \vee (d_2 \rightarrow d_k)...\vee (d_i \rightarrow d_k)$ the logical variable d_k will take the associated fuzzy value: $\alpha_k = \min(\alpha_1, \alpha_2..\alpha_i) \cdot \mu_j = \max(\alpha_1\mu_1, \alpha_2\mu_2..\alpha_i\mu_i)$*

5. 6. Hierarchical approaches for reccurrent detection/diagnostic modelling **with RecSinFPN**
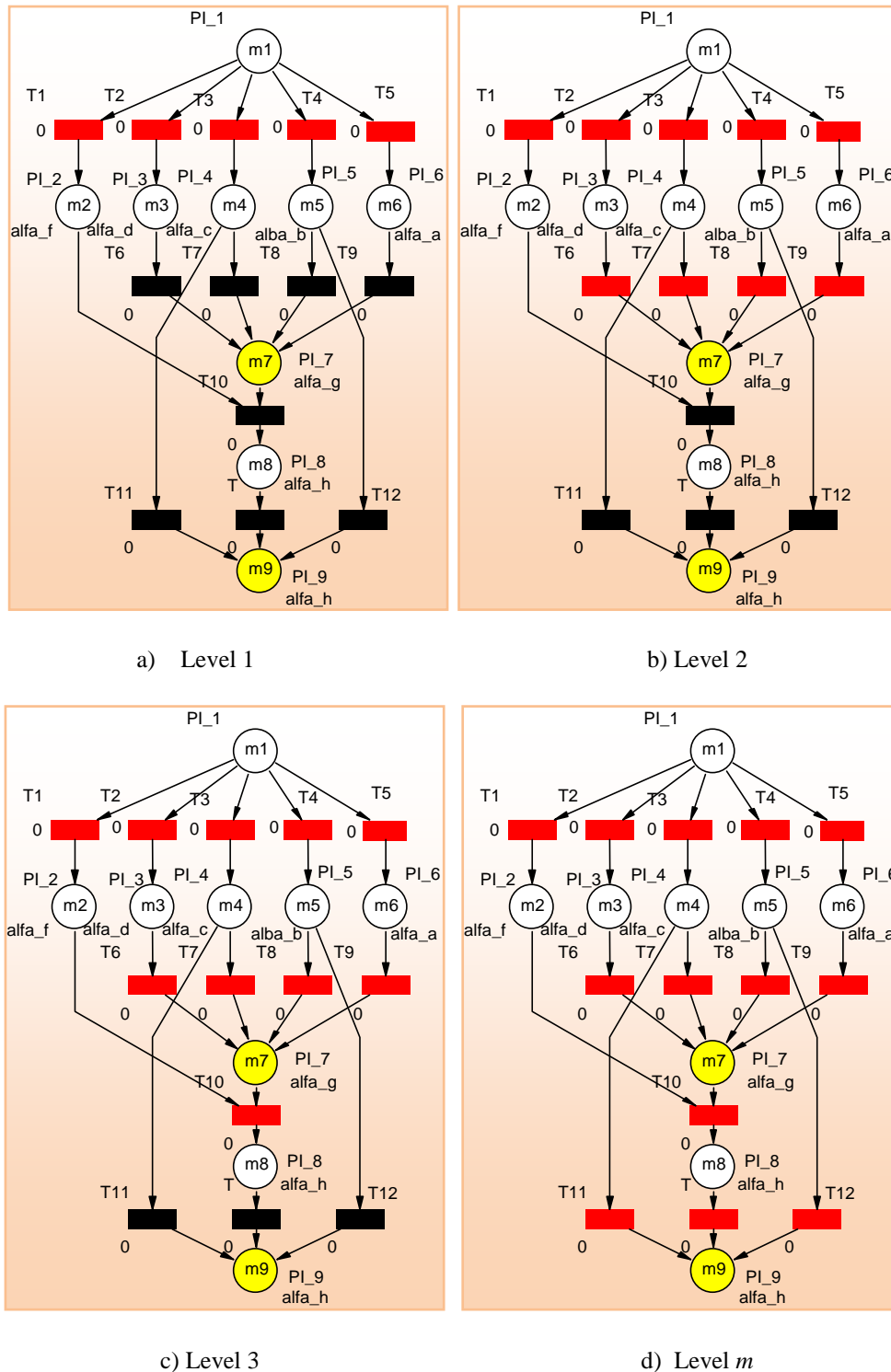
Figure 58. *Elementary SinFPN networks with m hierarchical levels successively activated*

In order to implement the recurrent detection, we propose the hierarchical structure represented in Figure 54b, Figure 60. In this approach, the faults tree is modeled with the *SinFPN* tool (Figure 54a). In this network, we shall identify the *m* hierarchical levels. Each level describes

the system evolution for a specific fault state. Each fault state is located in the nodes of each horizontal level. We will refer to this network as the *Elementary SinFPN network*, as it constitutes the node of the distributed hierarchical structure proposed for the recurrent detection function models.
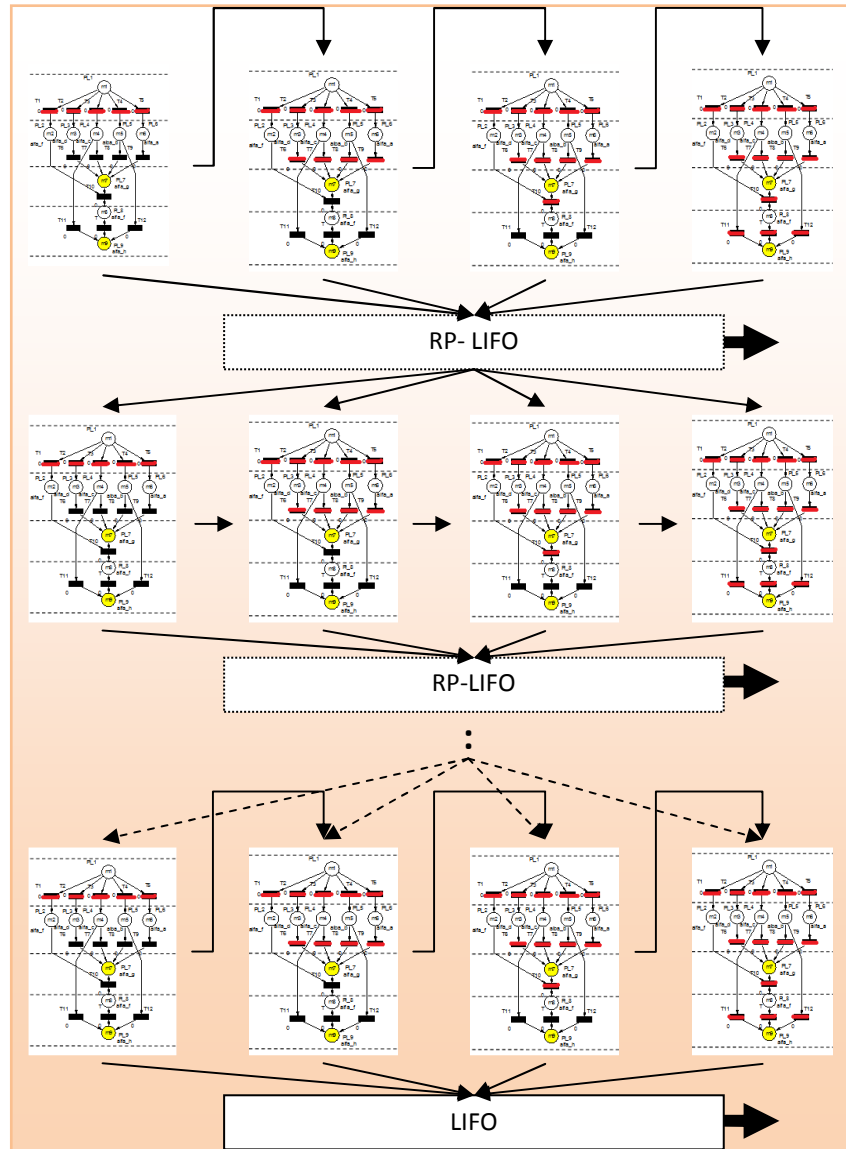
Figure 59. *Structure of RecSinFPN. The typology of component modules*

For an elementary *SinFPN* network, we define *m* hierarchical sublevels which correspond to a possible order of critical faults occurrence. This model shall be used repeatedly within the distributed hierarchical structure. For each horizontal level, we shall repeat the *SinFPN* model *m* times. The *SinFPN* placed in (i, j) node has the following characteristics: the temporal window, associated to direct detection, is ΔT_i. The elementary *SinFPN* model has activated the first "*j*" levels for the synchronization with direct detection model. Each level is defined by a linear logic dependence. The other levels of the model consist of autonomous *SinFPN* transitions. The junction between levels is performed by a PN module that implements the LIFO comunication principle (last input-first output) (Figure 59).

From the logical expression of FT results *m* elementary *SinFPN* models that have external synchronization events successively associated into the interface. These events correspond to a certain degradation state, described by FT.

Figure 58.a) shows the *SinFPN* model which is only associated with the external events related to the first level. The other transitions are autonomous. In Figure 58.b), the first two levels expected the synchronization signals from the direct detection model. Finally, all the *m* levels are simultaneously activated.
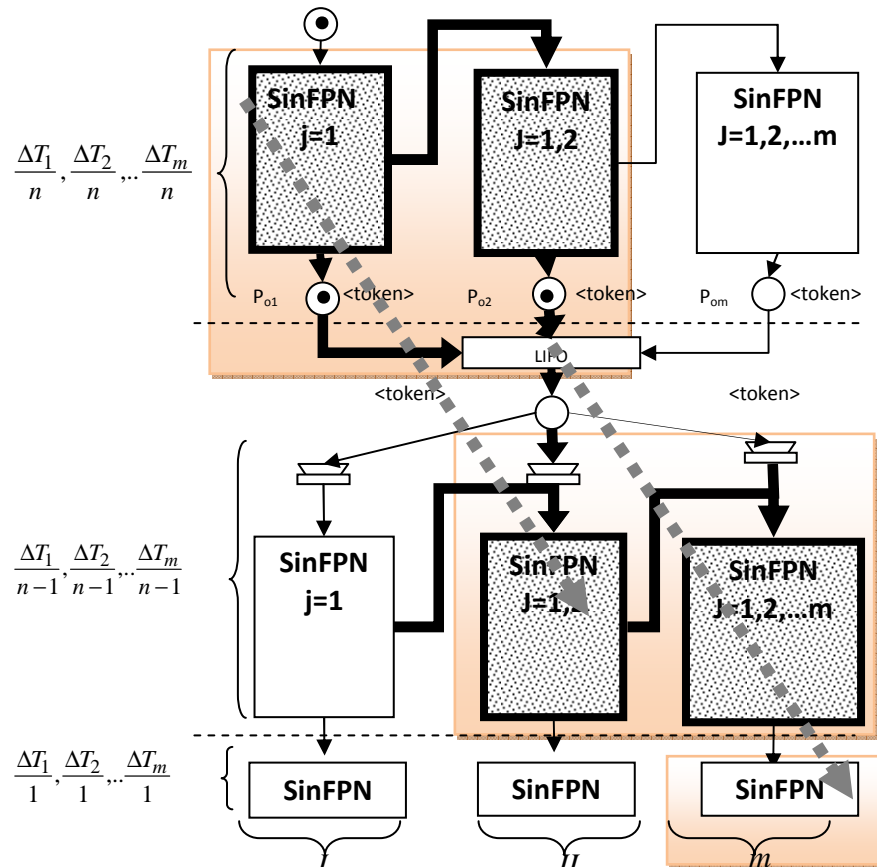
Figure 60. *Recurrent detection function* modelling *in distributed systems using PNetSinFREC and OOPN*

The distributed hierarchical structure is defined by $m \times n$ hierarchical levels. The *n* levels have different durations associated to each temporal window. The set of these durations is:

$$\left\{ \frac{\Delta T_1}{n}, \frac{\Delta T_2}{n}, .. \frac{\Delta T_m}{n}, \frac{\Delta T_1}{n-1}, \frac{\Delta T_2}{n-1}, .. \frac{\Delta T_m}{n-1}, ... \frac{\Delta T_1}{1}, \frac{\Delta T_2}{1}, .. \frac{\Delta T_m}{1} \right\}$$

Each node contains an *elementary SinFPN* as a certain scenario for a new fault occurrence:
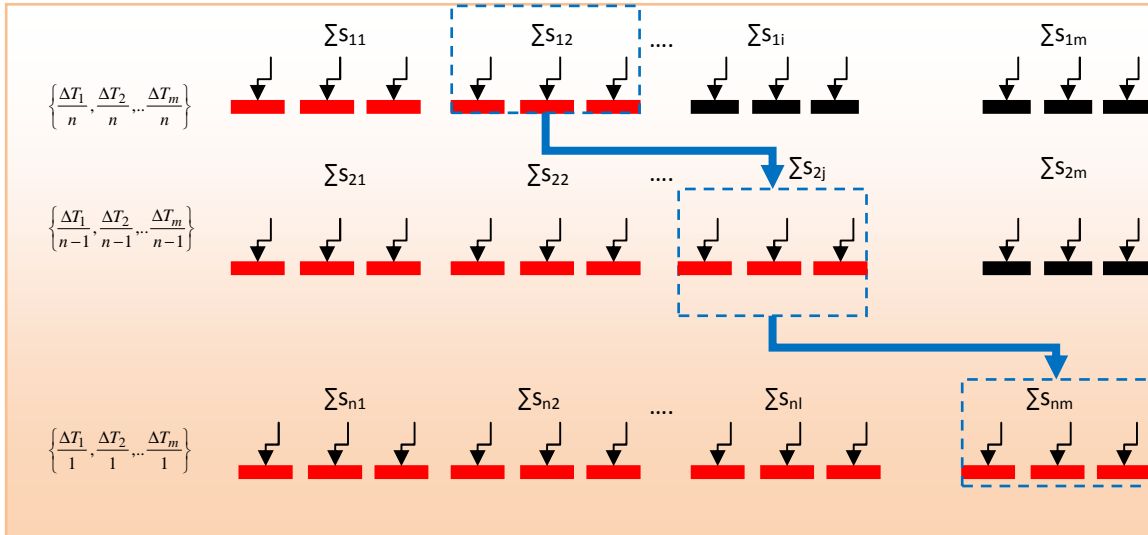
Figure 61. *Refining direct detection within the RecSinPN model*

Within each interval, is expected occurrence of a certain aggravating context. For exemple, if we consider the FT expression:

$$F = \left[\left\{(a+b+c+d)\cdot e\right\}+b+c\right]$$

The logical corresponding expression is:

$$F = \left(\left(\underbrace{\overline{(a\ \mathbf{OU}\ b\ \mathbf{OU}\ c\ \mathbf{OU}\ d)}}_{\overline{ds1}=g}\right)\ \mathbf{ET}\ e\right)\ \mathbf{OU}\ b\ \mathbf{OU}\ c$$

$$\underbrace{\phantom{\left(\left(\overline{(a\ \mathbf{OU}\ b\ \mathbf{OU}\ c\ \mathbf{OU}\ d)}\right)\ \mathbf{ET}\ e\right)}}_{\overline{ds2}=f}$$

$$\underbrace{\phantom{\left(\left(\overline{(a\ \mathbf{OU}\ b\ \mathbf{OU}\ c\ \mathbf{OU}\ d)}\right)\ \mathbf{ET}\ e\right)\ \mathbf{OU}\ b\ \mathbf{OU}\ c}}_{\overline{ds3}=h}$$

The elementary *SinFPN* are:
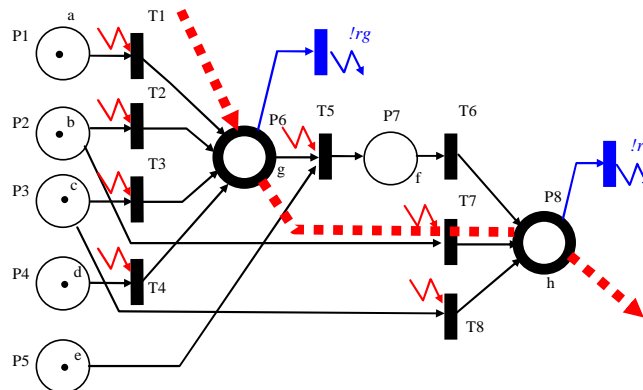
Figure 62. *The SinFPN corresponding to F expression*

The set of places $\{P_6, P_7, P_8\}$ represents the degradation contexts. The system arrives in P_6 degradation state, if the logical expression: $F1 = a \cup b \cup c \cup d$ becomes true. The P7 state is reached if the e fault is occurred: $F2 = (a \cup b \cup c \cup d) \cdot e$. Finally, for P_8 state the b or c faults must occure: $F3 = [\{(a+b+c+d) \cdot e\} + b + c]$.

Once a fault state is achieved, the model evolves horizontally, until it arrives in the corresponding *SinFPN* node. This first incursion is made between the nodes with successive durations: $\left\{ \frac{\Delta T_1}{n}, \frac{\Delta T_2}{n}, .. \frac{\Delta T_m}{n} \right\}$. Once placed in this node, the token drops one level below, towards the corresponding node (LIFO mechanism). In this point, it waits for the next fault occurrence. For each jonction place, the system is able to conserve the past evolution through dedicated P* places. Each token is associated with the description of a token object class.

The *SinFPN* model applies the temporal fuzzy descriptions proposed for each transition of the model [Min, 09b], [Min, 09c]. After the firing of the transition, each place located in its postcondition has a credibility value corresponding to the fault gravity associated to it. Vertical displacement within the model refines the diagnostic result, because each hierarchical level of SinFPN has increasingly smaller durations associated to it.
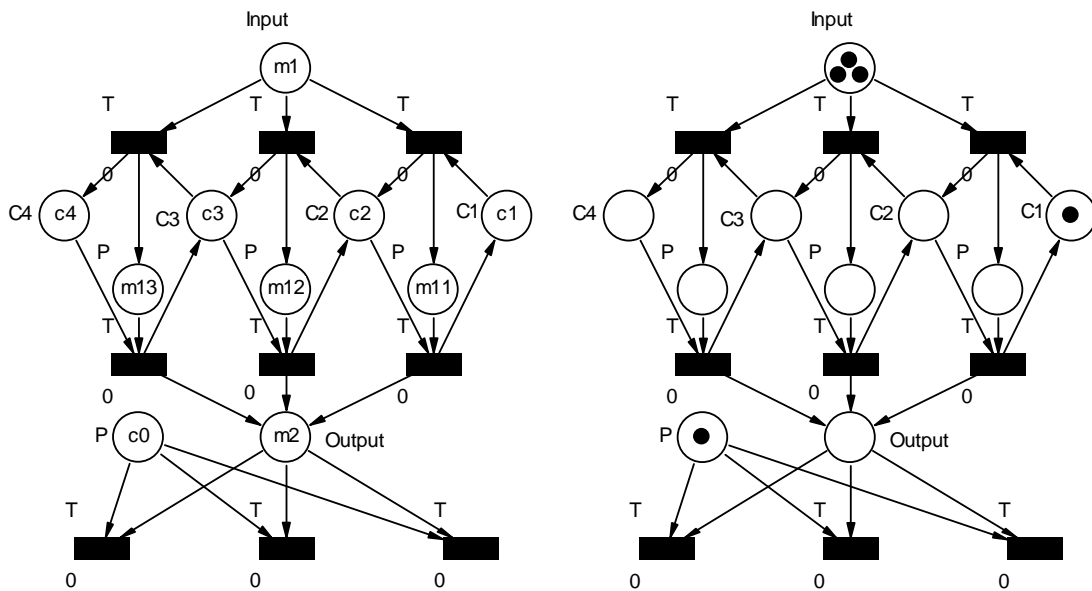
Figure 63. *PN modelling of the LIFO relation for input-output functions*

The LIFO module only handles the last entry *"j"* in the stack (level $P^* = \{P_{o1}, P_{o2}, .. P_{om}\}$).

The place P_{oj} corresponds to *"j"* horizontally node on the previous level of *SinFPN*. That indicates the degradation state reached in the previous level. The validation of the *"token.level == k"* condition places the current state of the diagnostic system into *"j"* node, corresponding to the next level.

According to the definition of OOPN, places $P^* = \{P_{o1}, P_{o2}, .. P_{om}\}$, have the following values associated to them:

$$\begin{cases} P_{o1}.level = 1 \\ P_{o2}.level = 2 \\ \ : \\ P_{om}.level = m \end{cases}$$
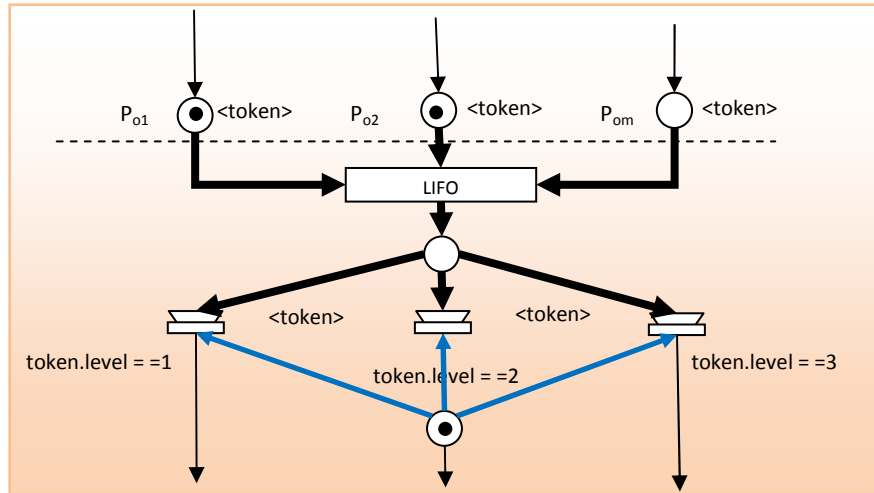
Figure 64. Modelling *of the recurrent aspect using OOPN*

The hierarchical structure is generated by the supervision probability of events occurrence. The events with a high probability of appearance (faults in the case of detection) shall be read in the upper levels of the structure. The events with a low probability of appearance shall be signaled in greater temporary windows, corresponding to the inferior levels of the distributed hierarchical structure. By using the LIFO mechanism, the system advances on the hierarchical levels of the *RecSinFPN*, in places which preserves the information from the previous level. Thus, the recurrent aspect of the network has been modeled. The fuzzy aspect is contained by the elementary *SinFPN* network. The monitoring system expects the occurrence of the event (Figure 58, Figure 60). In the hierarchical structure of RecSinFPN, after each action switching to the next node, the new degrees of credibility for logical propositions of SinFPN will be established.

Chapter 6

Applications of the Recurrent Synchronized Fuzzy Petri Nets

6. 1. Application of the RecSinFPN for flexible manufacturing system monitoring

RecSinFPN was tested on Sormel manufacturing system (FEMTO-ST, AS2M Department, Besancon, France) when has been the monitoring system implemented. The results of this research continues previous research [Min, 2009a], [Min, 09b], [Min, 09c], [Min, 09d], [Min, 09e].
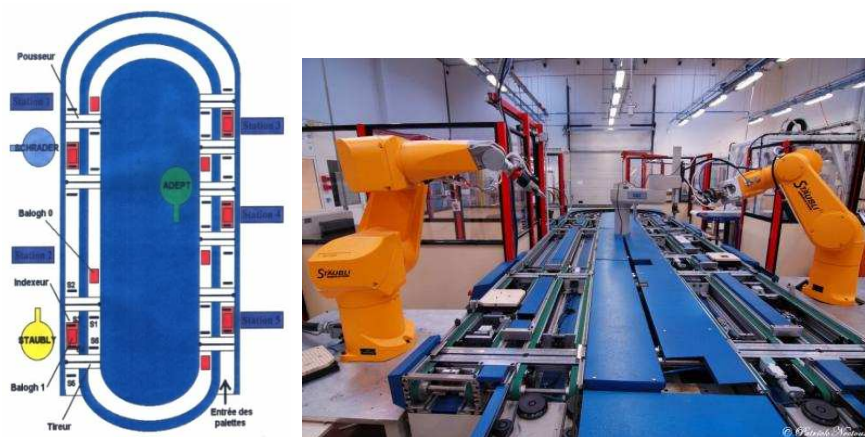
Figure 65. *The manufacturing system SORMEL*

Sormel manufacturing system is composed of five workstations equipped with robotic manipulators. The transport system, based on pallets transfer, is organized in double rings (internal and external) (Figure 65). The inner ring allows the movement of pallets between workstations. The outer ring is dedicated to tasks processing.
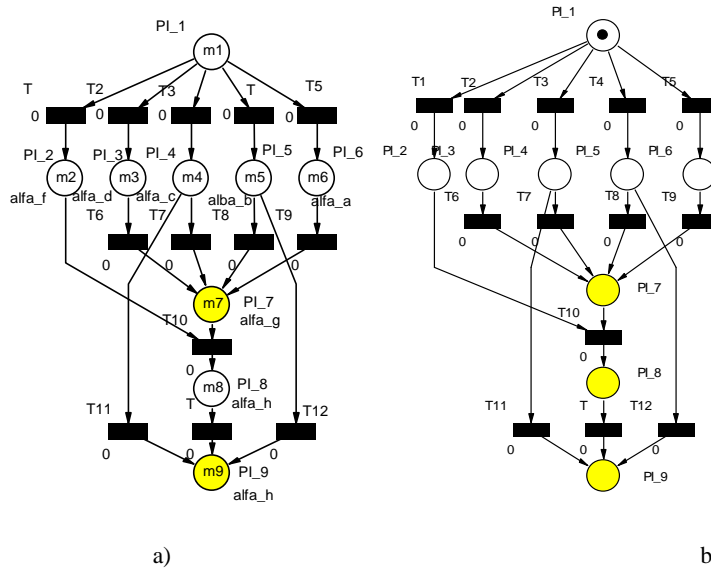
Figure 66. a) *Structural and b) marked elementary RecSinPN corresponding to FT*

Each workstation is equipped with pneumatic actuators (pusher, indexer, and gunner), electric actuators (stoppers) and inductive sensors (proximity sensors). An inductive system for reading/writing can also identify and locate each pallet, therefore each batch in the flexible system. The inner ring allows the movement of pallets between stations. The outer ring is dedicated to tasks processing.

We consider the logical expression F corresponding to faults propagation. F is named the faults tree (FT) or FT (*fr: FT*) of the production system [Min, 11b](Figure 40):

$$F = \left[\left\{(a+b+c+d)\cdot e\right\}+b+c\right]$$

where $+$ and $*$ operators represent the union or the intersection of logical variables $\{a,b,c,d\}$:

R1: *IF (a OR b OR c OR d)   THEN g   (FC=μ_{R1})*
R2: *IF (g AND e)   THEN f   (FC=μ_{R2})*
R3: *IF (f OR b OR c)   THEN h   (FC=μ_{R3})*

a)
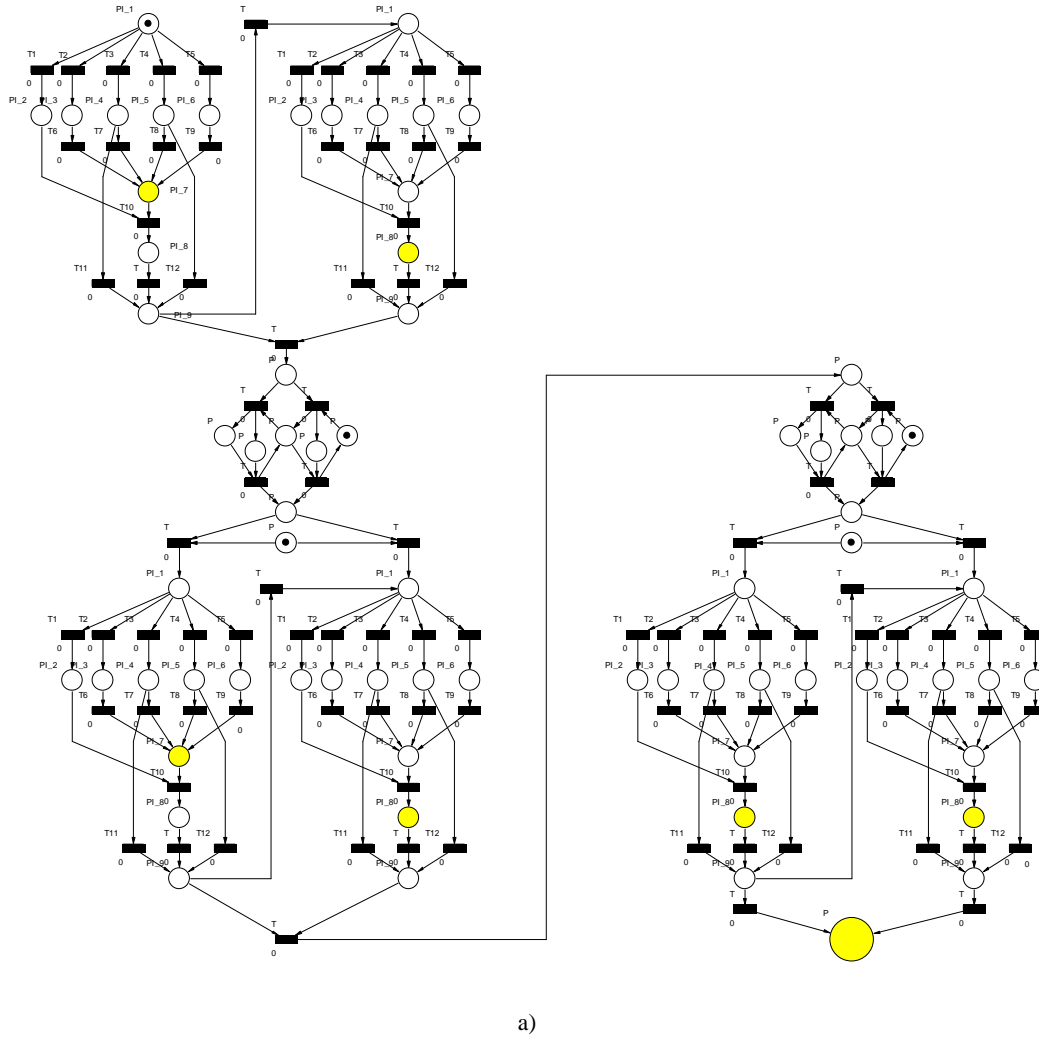
Figure 66. a). *Marked hierarchical monitoring system*

For faults that appear in the F expression, the following linguistic variables have been associated: $\{d_1, d_2, d_3, d_4\}$:

$$F = \underbrace{\left(\underbrace{(d1 \cup d2) \cap d3}_{ds1}\right) \cup \underbrace{(d4 \cap d1)}_{ds4} \cup \underbrace{d3 \cap \underbrace{(d1 \cup d4)}_{ds2}}_{ds3}}_{ds6}$$

The expression of F results from the logical analysis of the successive faults occurrence. The *Elementary RecSinPN*, for modelling the fault occurrence and its propagation in the monitored system, is represented in Figure 66.

According to the *RecSinFPN* definition, we propose a hierarchical distributed structure which makes the prediction of the degradation state for the monitoring system. The monitoring system describes, through repetitive experiments, *the critical path of fault occurrence*. Each nodes of *RecSinFPN* is correlated with one of the rules of faults propagation in FT.
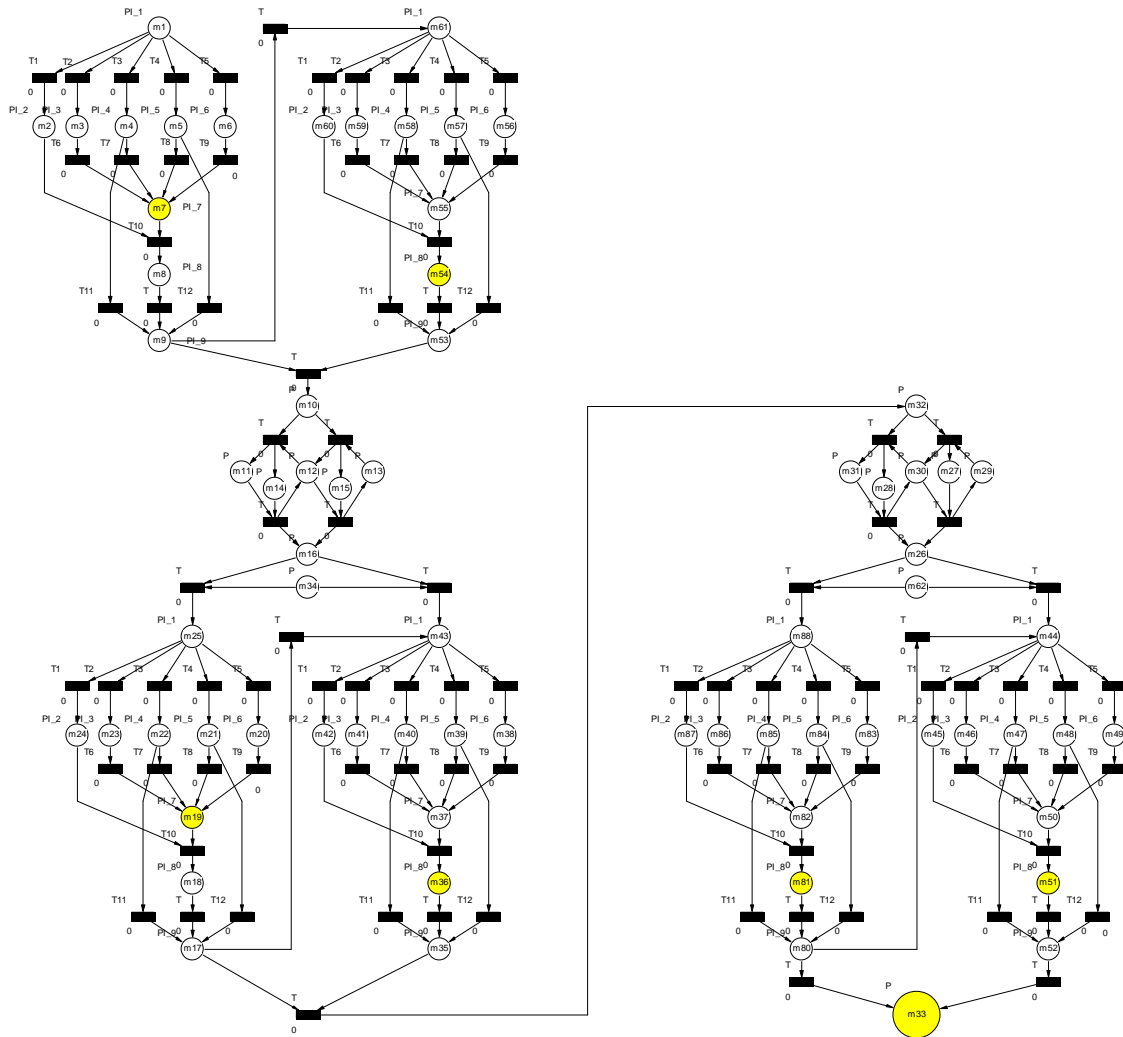
b)

Figure 67. a) *Marked and b) structural hierarchical monitoring system*

Both horizontal and vertical levels modelling by *Elementary RecSinFPN* the detection function according to the causality description of FT. For example, let us considered two categories of faults with successive occurrence. Their appearance can be modeled through the horizontal level. The LIFO module injectsed the token into the corresponding node on the next level (Figure 67).

The process is iterative and differs from the previous level only through the temporarily interval associated to the current level. The detection of the external events is restarted from the current node. If new categories of external events (faults) can be read, the network evolves again horizontally. The last state is retained by the LIFO system, which sends the information on the next level, in the corresponding node, etc.

The LIFO module, generally situated after the horizontal level *k*, is projected so that it may successively receive a number of *m* information, corresponding to the *m* modules *Elementary RecSinFPN* arranged on horizontal levels (Figure 68). The hierarchical structure situated on the inferior level *k-1* will only use the last information in position *m16*, due to the control variables *m17* or *c0*. (Figure 68, Figure 64).
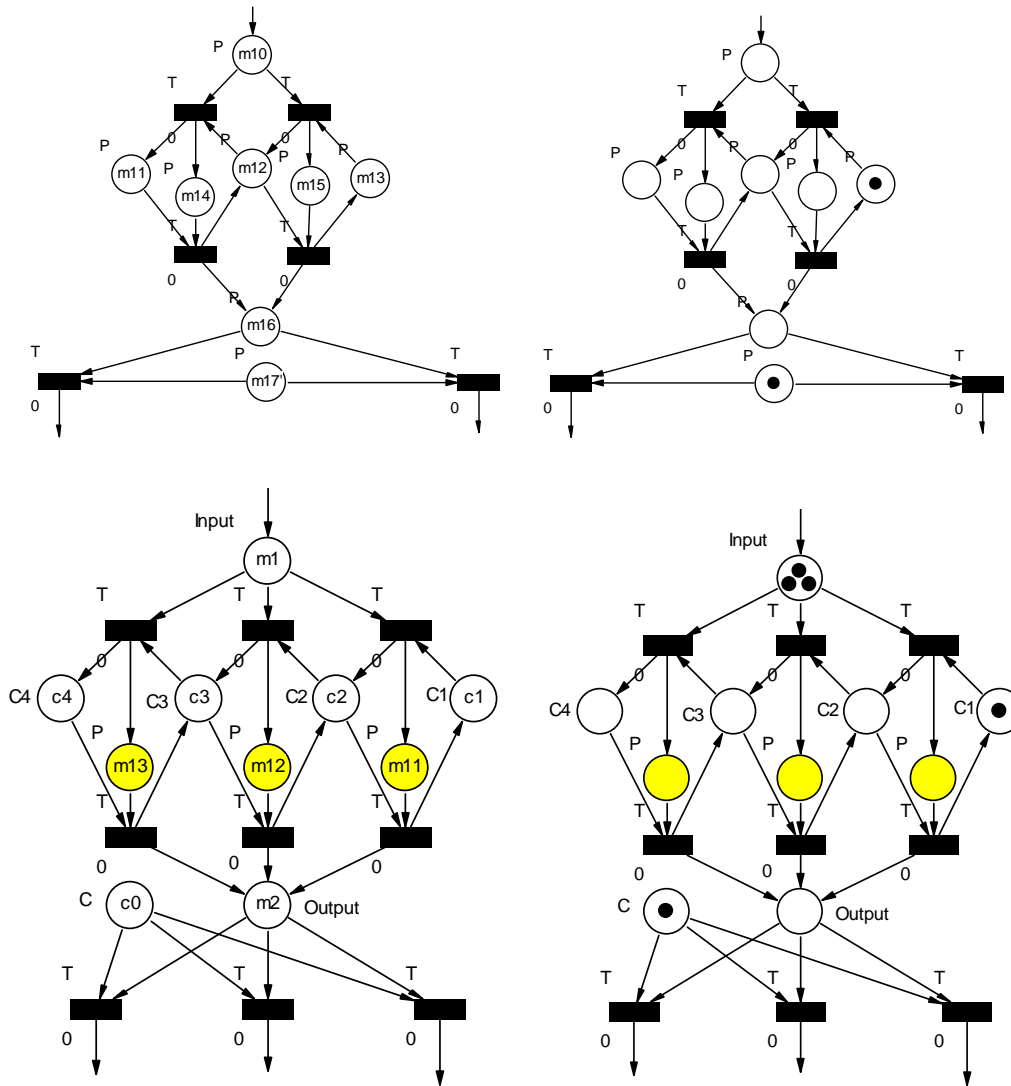
Figure 68. *PN_LIFO module corresponding to a hierarchical structure RecSinFPN with m=2 and m=3*

6. 2. Application for manufacturing systems served by collaborative robots monitoring

To illustrate the interest for the application of *RecSinFPN* dedicated to recursive monitoring, we proposed the study of monitoring and control systems for manufacturing systems served by collaborative robots monitoring. An manufacturing line is a flow-oriented production system where the productive units perform operations on workstations, which may be configured as serial, parallel, circular, U-shaped, cellular or two-sided lines. The work pieces visit stations successively as they are moved along the line, usually by some kind of transport system, e.g, a conveyor belt. The general approach will be customized for two *Mechatronics lines HERA&Horstmann* (Figure 69)
.
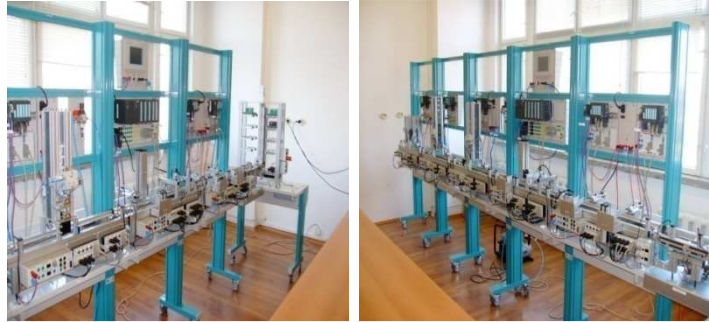
Figure 69. *Mechatronics lines HERA&Horstmann*

Generally, the autonomous manufacturing systems are served by several collaborative mobile robots. The proposed approach will be customised for two autonomous assembling mechatronic lines (Figure 69) served by a single mobile robot. Thus, the two mechatronics lines work as complementary systems in terms of resources availability.
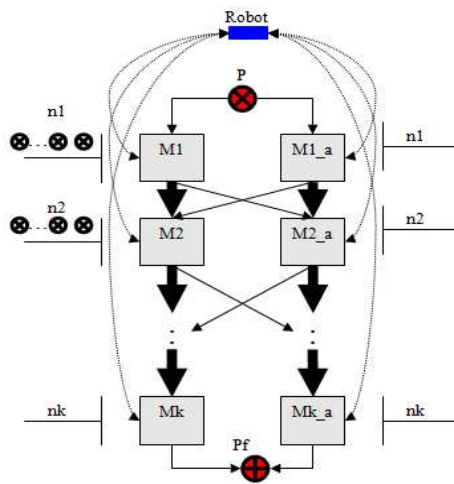
Figure 70. *Manufacturing systems served by a single mobile robot*

a)   b)
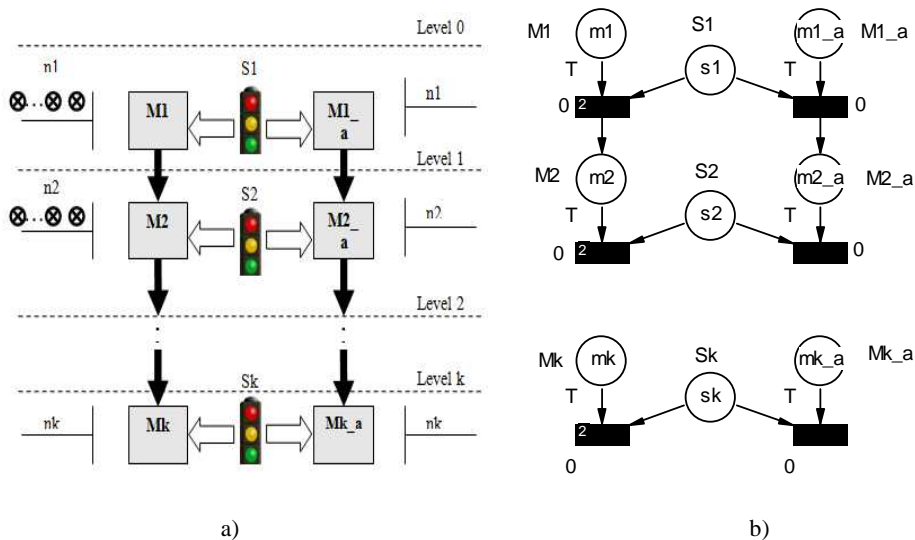
Figure 71. a) *The diagram and b) the PN model corresponding for the interface between supervisor and manufacturing systems*

The two systems are autonomous with parallel operations (Figure 69) served by collaborative robots. Because they use the collaborative robots, the two systems work in complementary mode when resource sharing is necessary to avoid bottlenecks (Figure 70).

For manufacturing systems we consider the following restrictions:

— *both manufacturing systems are identical in terms of available resources (similar resources in workstations) Figure 71 a)*
— *each workstation M_k has a specified length for the waiting queue (workpiece in course of execution): n_k*
— *if the workstation M_k fails or if the number of waiting workpieces exceeds the limit n_k, then the excess workpieces are redirected by the mobile robot toward alternative workstation M_{k_a} . The workpiece transport is performed by the nearby mobile robot.*
— *the collaborative mobile robots (R) servicing the complementary workstations and come back in the parking area.*
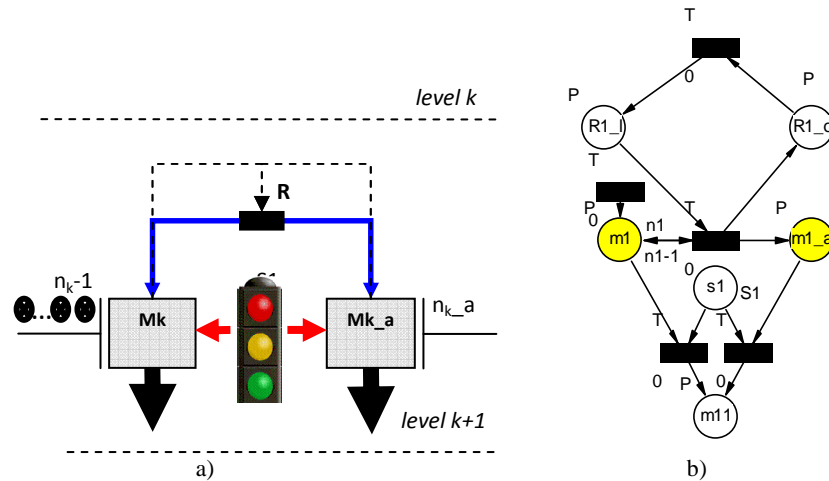
Figure 72. *a)The diagram and b) the PN model corresponding to the level k of the monitoring system*

The supervisor S_k monitors the availability of resources for main flow. If a resource M_k reaches the blockage state, the supervisor S_k directs the operational flow toward alternative resource M_{k_a} (Figure 72). For this reason, the model PN for the monitoring system has different priorities for complementary activities assigned to it (Figure 71 b)).

The Figure 73 c) represents the generalized PN monitoring model for two manufacturing systems composed of *{M1, M2, ..Mk}* / *{M1_a, M2_a, ..Mk_a}* workstations and served by a single robot. If a blockage is identified at the workstation M_k (the queue size exceeds *nk* workpieces), the supervisor S_k switches the production to alternative workstation M_{k_a}. The workpieces follows a route through workstations in accordance with the gamma operations of manufacturing.
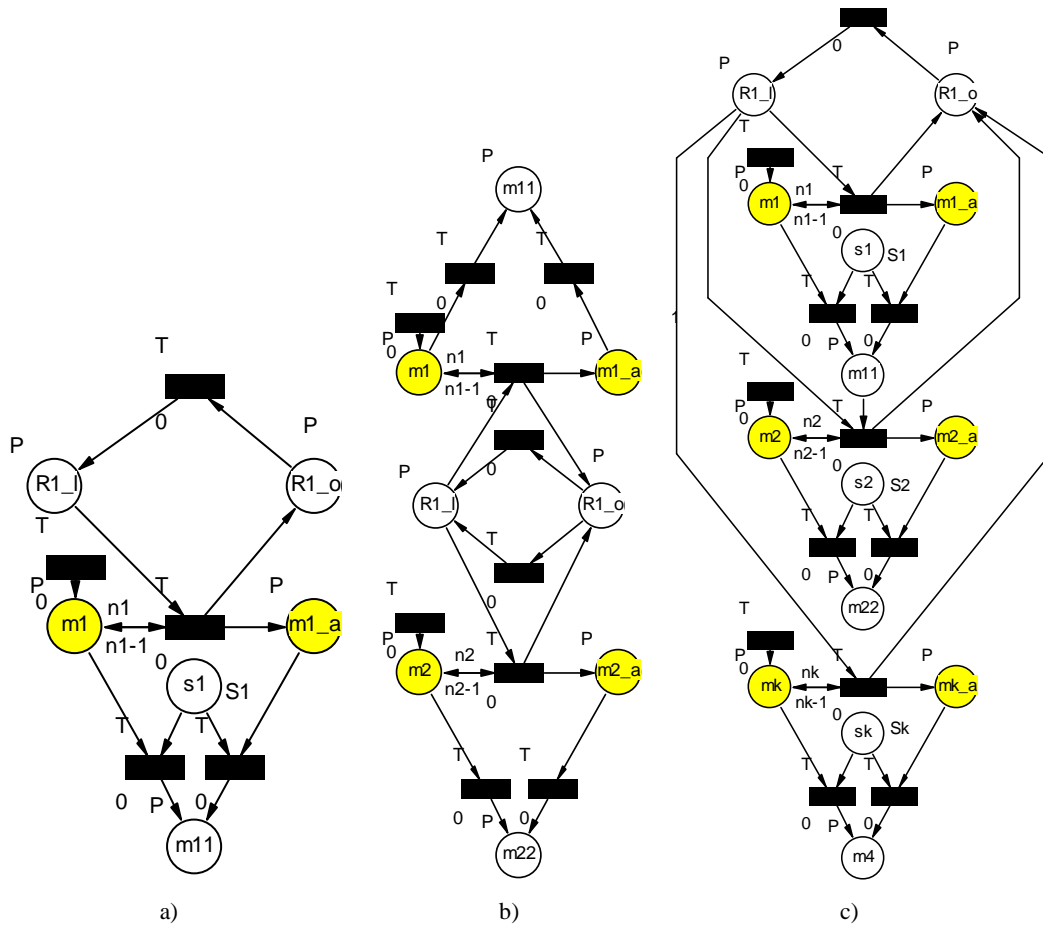
Figure 73. *PN model corresponding to two manufacturing systems composed of a) one workstation b) two workstations c) k-workstations served by a single mobile robots*

The refining of a monitoring function requires its decomposition in successive actions (Figure 74) corresponding to successive failure tests. The durations allocated for monitored transitions corresponds to each M_k workstation activity and it is in accordance with the corresponding gamma operations of manufacturing . For bottlenecks testing, the monitoring action will be repeated in time, at increasingly smaller intervals.

We must specify that hierarchical supervision PNs – *RecSinFPN,* function only in a synchronization relation with the process monitored in real time and with the PN model destined for direct detection modelling (Figure 17). The direct detection model receives blockages and sends synchronization signals with transitions associated with monitoring activities. Thus, supervisor S_k will be able to make a decision regarding the commutation to the available alternative resource.
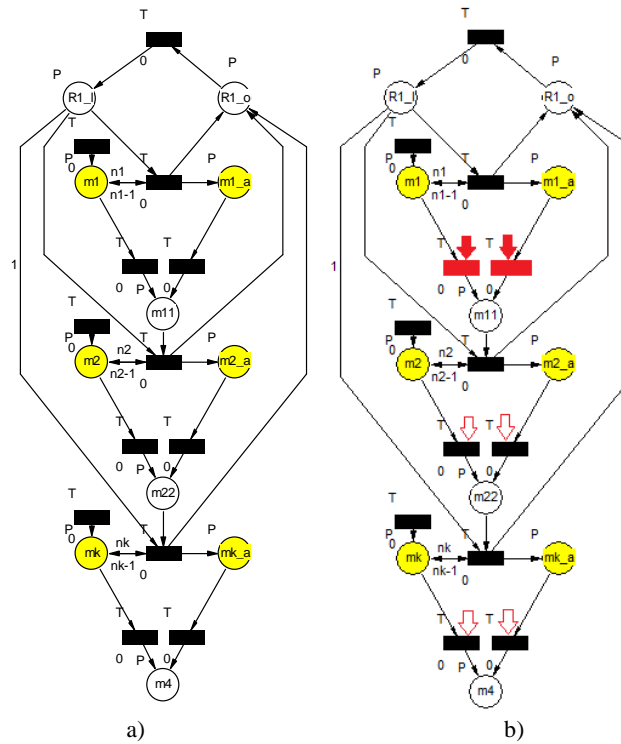
Figure 74 *a) Elementary RecSinFPN for two manufacturing and complementary systems served by a single mobile robot; b) monitoring system for complementary resources*

The recurrent execution of the monitoring function presupposes the existence of a PN structure with horizontally repeated execution.
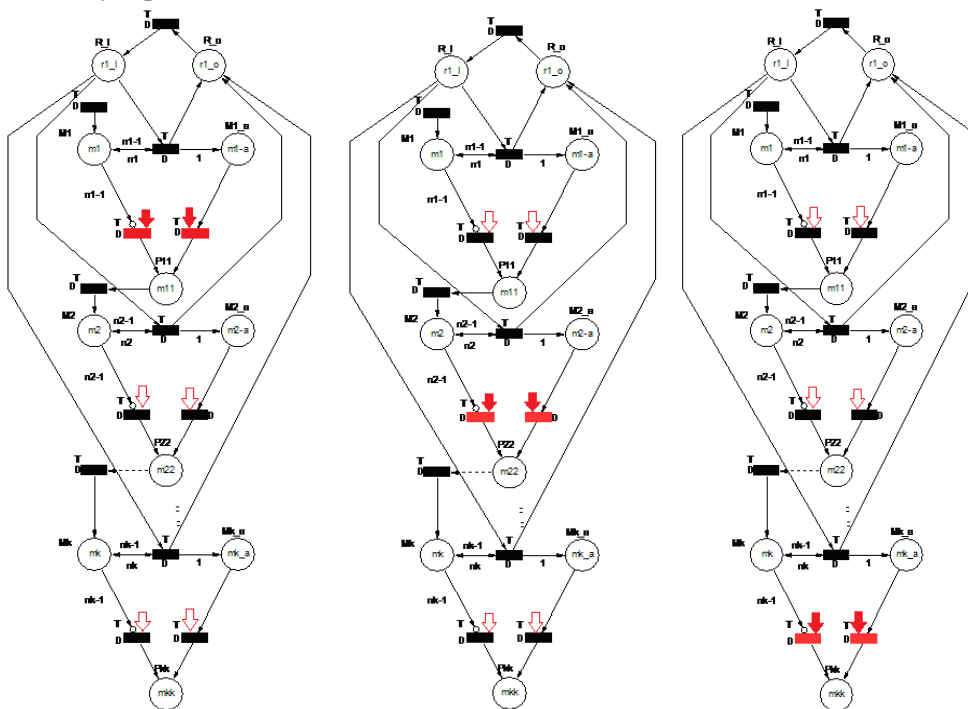
Figure 75. *Elementary RecSinFPN for successive monitoring of gamma operations*
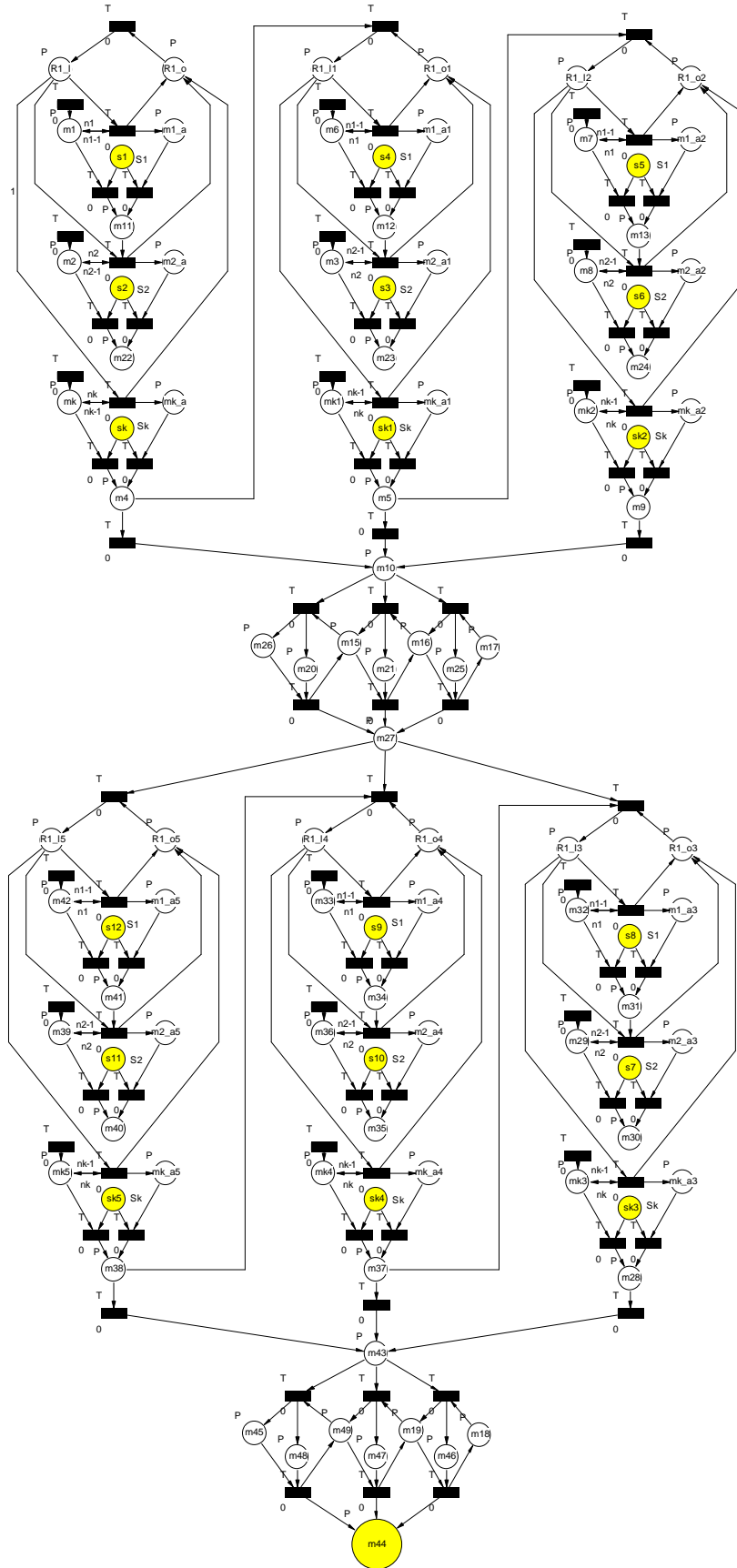
Figure 76. *RECSinFPN for intelligent hierarchical monitoring system*

The hierarchical structure RECSinFPN is interfaced with direct detection. Each module *Elementary RecSinFPN* is synchronized during the time allocated with the data sent by the RTP direct detection model. *Elementary RecSinFPN* modules are synchronized successively with direct detection by certain transitions which describe a specific rule of FT.

On the horizontal level of RecSinFPN structure, the possible fault states are described successively, in accordance with the rules set by FT. The FT's rules are found successively at the horizontal level of RecSinFPN, through Elementary RecSinFPN. The refining of the monitoring function is performed by a recurrence action on the next level. On this level it is takes the current state of the monitored system, according to the previous level, and resume again the action??. The whole action for horizontal synchronization and evolution of the model RECSinFPN is resumed, but for a smaller time window. For each new iteration, the new synchronization process starts with direct detection, but in increasingly smaller temporal intervals. The consequence of this mechanism is the refinement of the monitoring function.

Chapter 7

Modelling and Control of an Assembly /Disassembly Mechatronics Line Served by Mobile Robot with Manipulator

Assembly/disassembly manufacturing systems are real-time and complex control systems, which involve multiple operation conditions and tasks. Hybrid systems are currently the focus of considerable attention. The assembly/disassembly manufacturing lines served by mobile robots have hybrid characteristics, consisting of continuous dynamic behaviours and discrete event behaviours. Hybrid Petri Nets (*HPNs*) are tools used to model such systems ([Gho 08], [Vod, 12], [Min, 12]). The assembly/disassembly plans are made up of parts or subassemblies that are fitted together ([Alb, 98]). Particularly relevant research topics include assembly/disassembly representations, work-cell planning, sequence planning, etc.

Off-line task planning is a large area encompassing a diverse set of planning methodologies capable of producing a detailed operation plan, including planning sensory action, planning manipulator action, planning the trajectory of mobile robots ([Gas, 07]), rough motion planning, fine motion planning and other planning ([Fen, 08]). On-line planning addresses execution and reaction issues such as how to develop plans on-line, how to execute and monitor a plan developed off-line, and how to react to various situations that arise during plan execution ([Gan, 05]). These issues can be further classified into: plan monitoring, reactive scheduling, and behaviour-based action.

Conventional representation of a system model without constraints may result in a huge search space for feasible plans. Using this model, the task planner can determine the sequence of components that must be removed to achieve a specific sequence of tasks. If the target consists of disassembling a specific component, the task planner can provide the best sequence for reaching the specific component ([Moo, 01]). If the fully assembled product fails the quality test, the task planner provides the best sequence for completely disassembling the product. A comprehensive knowledge-based approach to disassembly task planning is required, which considers all aspects of complex interaction and domain knowledge subjected to technical and economic constraints [Dav, 10]. Development of knowledge based on a HPN model integrated with a sequence generation algorithm was successfully applied to modelling and planning of a flexible disassembly process and system at a high level. However, the typology of the autonomous mobile robot with manipulator, disassembly planning method, and task level planning, greatly improves the efficiency of the entire process and reduces the cost of product disassembly. Task specification in low-level task planning consists in changing models or operation sequences ([Hir, 99]).

It is proposed a Synchronised Hybrid Petri Nets (SHPN) model for an Assembly/Disassembly Mechatronics Line (A/DML) served by a Wheeled Mobile Robot (WMR) equipped with a

Robotic Manipulator (RM), together with an Assembly/Disassembly Line Balancing (A/DLB) model. Disassembly line balancing is used to find the set of tasks assigned to each workstation for each product to be disassembled. The problem is critical for minimising the use of valuable resources (such as time and money) invested in disassembly, and maximising the level of automation of the disassembly process and the quality of the parts or materials recovered ([McG, 07]). In this thesis, we consider a Disassembly Line Balancing Problem (DLBP) with a fixed number of workstations so as to maximise the value of recovered parts. [Lam, 02] emphasises that a disassembly process does not imply a reverse assembly process.

The A/DLB and SHPN models have been customised for an assembly mechatronics line, which assembles a 5-part product. Using the LabView platform, real-time control of A/DML served by WMR with RM is presented, based on A/DLB and SHPN models. These models provide a high-level description of the product to be disassembled. The aim is to assign the tasks to the disassembly line workstations so as to maximise the total value of the recovered parts. The disassembly operations are performed on the same assembly line, consisting of a number of linear configured workstations. The first workstation takes the product to be disassembled, and the parts are disconnected on different workstations. A cycle terminates, i.e. the product leaves the line, whenever all its required parts are disassembled.

The concepts of assembly/disassembly tasks are illustrated in a SHPN model, which complies with both aspects: the discrete approach for the elementary assembly/disassembly operations, and the continuous approach for displacement of WMR. Thus, the A/DML system becomes reversible and is served, during the disassembling process, by a robotic manipulator mounted on a mobile platform. The A/DML dynamics are determined by events, supplied by the control sequences of the automatic system, and by interaction with the WMR, which represents the continuous time part of the system. The considered system is a hybrid one and requires specialised tools for modelling. The hybrid model is elaborated using the dedicated modelling tool, HPN, described in [Dav, 10]. A SHPN model results from the combination of the SED model of the analysed system with the cyclic and continuous time of the WMR with RM.

7. 1. Preliminary remarks concerning A/DLB and SHPN models

The assembly/disassembly line is served by a WMR equipped with RM during the disassembly phase, Figure 77. The aim is to make the assembly/disassembly line balanced and reversible. Moreover, the mobile robot is used to carry the disassembled components to a proper storage warehouse.

7.1.1. Assembly assumptions

Assembly lines are special flow-line production systems, which are typical in industrial production of high quantity standardised commodities. According to [Cho, 98], there are several classification schemes for assembly lines, which take into account the nature of the products, operation modes and the nature of operation times. Corresponding to these classifications, the following assumptions hold concerning the assembly of mechatronics systems:

A.1. *The A/DML is a single-model line, by the nature of the product, paced line (transfers between the workstations are synchronous), by the operation mode, and deterministic line, by the nature of operation times (times known certainly).*

A.2. *There is a fixed number of stations, while minimising cycle time with respect to assembly line balancing of the A/DML.*

7.1.2. Disassembly assumptions

In [Alt, 08] and [Gun, 02], the DLB model is described for partial and complete disassembly,

respectively.
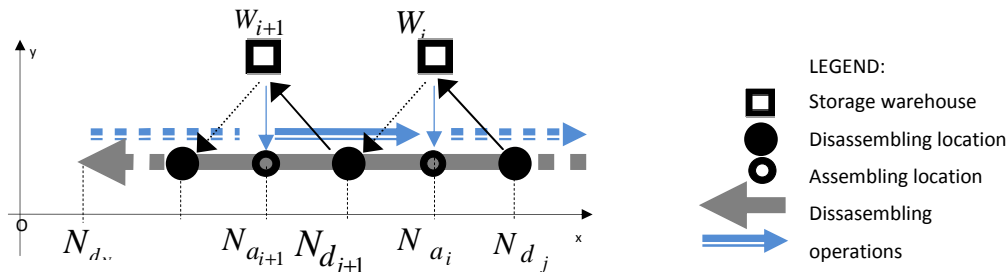
Figure 77. *Assembly/disassembly and storage warehouse locations*

The importance of disassembly lines in product recovery is discussed, as are also the various complications involved when creating an efficient disassembly line.

To elaborate the DLB model, the following assumptions must be made.

- A.3.   *The disassembly line is paced.*

- A.4.   *One type of product is disassembled, and each product has an identical configuration.*

- A.5.   *The complete disassembly process is considered, and all parameters, i.e., task times, cycle times, part demands, costs, are known with certainty, i.e., deterministic.*

- A.6.   *There are N workstations, linear-configured with a first workstation taking the product to be disassembled. The number of workstations is the same as the number of parts released by disassembly.*

- A.7.   *Each period is specified by a single part disassembly hence there are N periods where each period is referred to as an elementary cycle. The same tasks run in each cycle, but with different durations.*

- A.8.   *Each task is specified by its cost and processing time. The part releasing tasks have additional parameters, i.e., revenues.*

- A.9.   *Disassembly process starts immediately after the assembly process and after the product fails the quality test.*

- A.10.   *Storage warehouse places are identical to positions where assembly occurs.*

- A.11.   *In an assembly/disassembly operation, only one part is assembled/disassembled.*

- A.12.   *By convention it is assumed that the end product fails the quality test if it contains cylinders of different materials.*

- A.13.   *Once the last remaining part in the disassembly process has been transported to the storage warehouse, a new assembly process will start.*

- A.14.   *Mobile platform displacement, in each elementary cycle, is linear, without obstacles and with the same constant speed.*

    - Let *N* be the number of parts to be assembled and disassembled.

    - Let $N_{a_i}, i = \overline{1, N}$ be the assembly locations on the positive direction of the Ox axis.

- Let N_{d_j}, $j = \overline{1, N}$ be the disassembly locations on the negative direction of the Ox axis.

- Let W_i; $i = \overline{1, N}$ be the warehouse locations, which are identical to the assembly locations.

- Let $D\left(N_{d_j}, W_{N+1-j}\right)$ be the distance between the disassembly location, N_{d_j}, and the corresponding storage warehouse, W_{N+1-j}.

- Let $D\left(W_{N+1-j}, N_{d_{j+1}}\right)$ be the distance between the last storage warehouse W_{N+1-j} and the next disassembly location $N_{d_{j+1}}$.

- Let $D_{r_j} = D\left(N_{d_j}, W_{N+1-j}\right) + D\left(W_{N+1-j}, N_{d_{j+1}}\right)$ be the distance travelled by the mobile robot in the j stage of disassembly.

Variable $r = 1 + 3(j-1)$ indexes: a continuous place of the robot, Pcr, a continuous transition of the robot, Tcr, and a discrete transition of the disassembly process, Tdd.

Variable $k = 1 + 5(j-1)$ indexes a discrete place of the disassembly process, Pdd.

Variable $l = 1 + 4(j-1)$ indexes a discrete transition of the robot, Tdr.

7. 2. A/DML served by WMR with RM

7.2.1. Hardware description

The general approach will be customised for an A/DML mechatronics line, HERA&Horstmann, shown in Figure 78, Figure 79, Figure 80.a and Figure 80.b, which assemblies a five-parts piece, shown in Figure 80.c and Figure 80.d. The WMR, Pioneer3-DX, has an odometric system, two driving wheels, and one rear free wheel. Also, an on-board embedded microcontroller is able to read position information and send it, via a WI-FI link, to a remote PC according to a specific protocol. The remote PC computes control input and sends it to WMR. Also, the remote PC sends the data to the assembly line PLC ([Pen, 03]). The WMR is equipped with a RM with three articulations and one gripper paddle. The assembly/disassembly manufacturing flexible line is equipped with a SIEMENS Simatic S7-300 PLC (Programmable Logic Controller), with 5 distributed modules connected by Profibus. The flexible line includes five individual workstations with different tasks: carrying and transporting, pneumatic workstations, conveyor belt, sorting unit, test station and warehouse. The work part carrier is used for carrying and transporting the four-piece work part on a conveyor belt system. The work part carrier is equipped with 6-bit identification, which provides a large number of possible codes, read out by inductive sensors. The four-piece work part enables workflow operations such as assemblies, testing, sorting, storage, and disassembling. The components to be assembled are (Fig. 4c and 4d): work part carrier (base platform) (1), body (2), cover (3), metal cylinder (4) and plastic cylinder (5).

7.2.2. Task planning

The assembly/disassembly operation can be broken down into a sequence of elementary assembly tasks coupled in parallel with work-piece positioning tasks along the conveyor, as in [Cho, 98], [Gan, 05], and [Rad, 11] and [Rad, 12]. The hybrid disassembly strategy is based on the hierarchical model proposed in [(Kal, 08] and [(Rad, 11)], which uses a graph representation of the product in which component relationships are expressed by means of arrows. The hybrid

disassembly strategy is based on the hierarchical model proposed in [Sel, 99], [Min, 11b], [Rad, 12] [Min, 12a], which uses the general representation in Figure 77. Figure 81 presents the distances between disassembly locations and storage warehouses of the A/DML served by WMR with RM. WMR carries the component from the place where disassembly occurs to the appropriate storage warehouse. Figure 82 shows the task planning of 5 parts and their transport by WMR.

7. 3. SHPN model of an A/DML served by WMR equipped with RM

7.3.1. Structure of the SHPN model
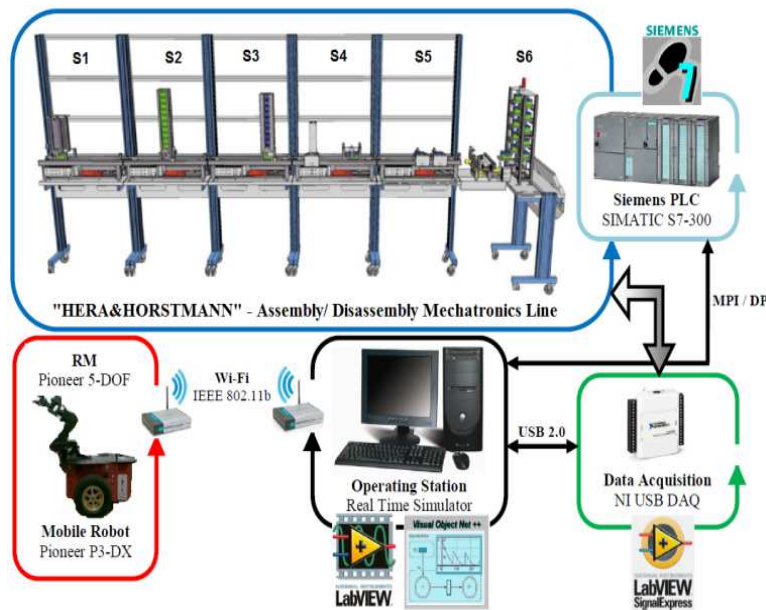
Figure 78. *Control structure of A/DML Hera&Horstmann served by WMR with RM.*

The hybrid aspect of the model is determined by variables related to distances travelled by the robot. These distances are considered between places where disassembly occurs and places where storage warehouses are located. These variables vary according to whether speed is constant or variable, a variation based on the mobile platform speed between A/DML locations.
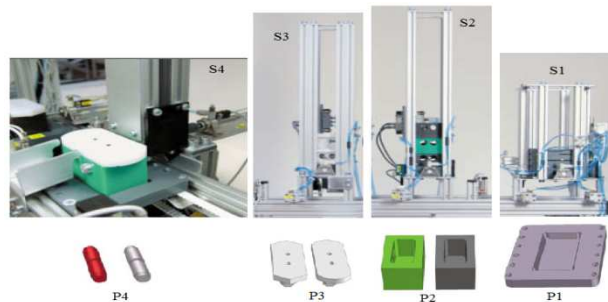
Figure 79. *Assembly workstation storage warehouses, assembly parts.*

To develop a global assembly and/or disassembly model, we shall consider the hybrid aspect of the assembly/disassembly process served by the platform. For modelling we shall use Timed Hybrid Petri Nets (THPN), [Dav, 10], which integrate the discrete appearance of the assembly/disassembly process with the continuous appearance of moving of the WMR and handling of components by the RM. The entire model is of the SHPN type as it is interfaced with external events for synchronisation in a modelling/simulation approach useful in real-time control.

| (a) | (b) | (c) | (d) |
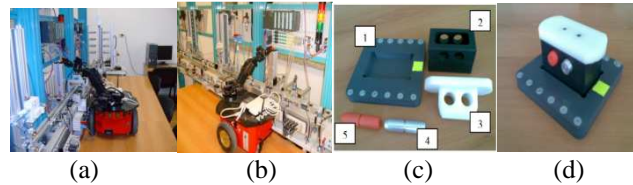
Figure 80. *(a) A/DML served by WMR, Pioneer 3-DX, equipped with RM, (b) Pioneer 5-DOF Arm; (c) parts; (d) assembled product.*

The SHPN structure, in Figure 83, and the SHPN representation by blocks in Figure 84 are obtained by modelling assembly/disassembly and continuous service assistance, for disassembly operations, performed by a mobile platform equipped with a manipulator. SHPN morphology results in integration of three PN models, each of which has a specific typology: TPN (Timed PN), SPN (Synchronised PN), and THPN (Timed Hybrid PN). These models describe the following automatic operations:

- *Assembly/storage in warehouses (TPN typology);*

- *Disassembly of damaged products (SPN and TPN typologies);*

- *Service assistance, during the disassembly process, performed by the mobile robot equipped with a manipulator (THPN typology).*
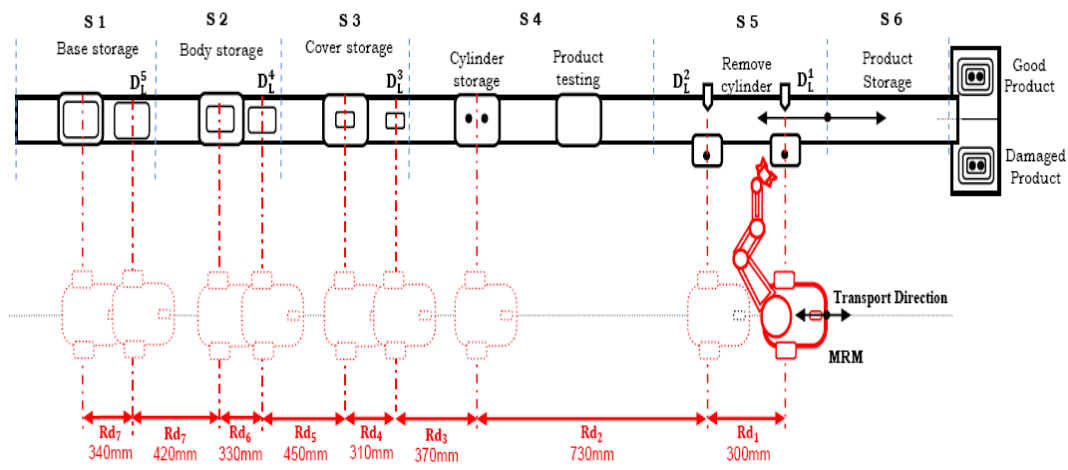
Figure 81. *Assembly/disassembly mechatronics line of a 5-part product, served by the WMR equipped with RM*
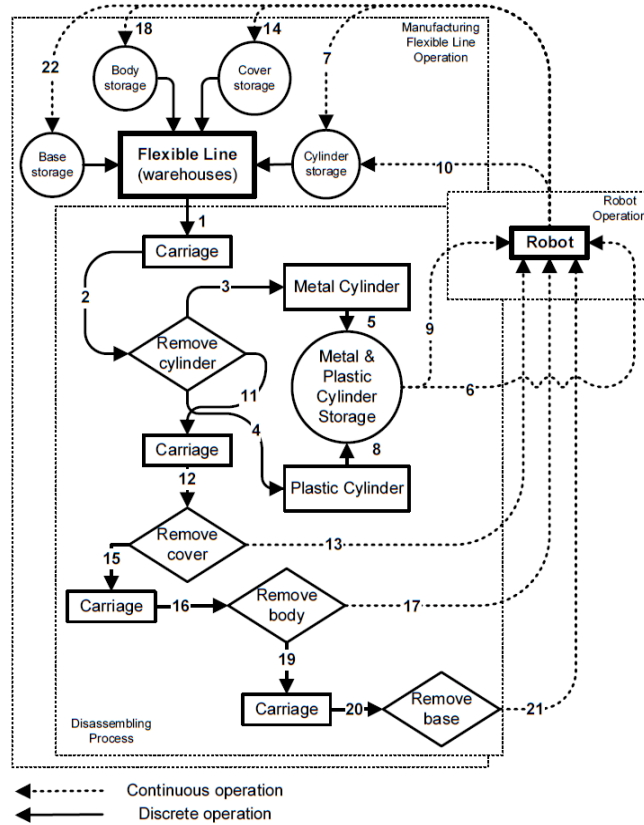
Figure 82*. Disassembly task scheduling*

7.3.2. Assembly/Disassembly repetitive sequences

Figure 85 shows an elementary TPN model corresponding to an assembly operation. Figure 86 shows the generalised TPN model corresponding to the assembly process, which includes a sequence associated with the quality test for the end product. During the disassembly process, a repetitive sequence can be identified, associated with a single disassembly operation and service assistance of WMR equipped with RM. These can all be modelled using a SHPN, known as an elementary SHPN, as shown in Figure 87.
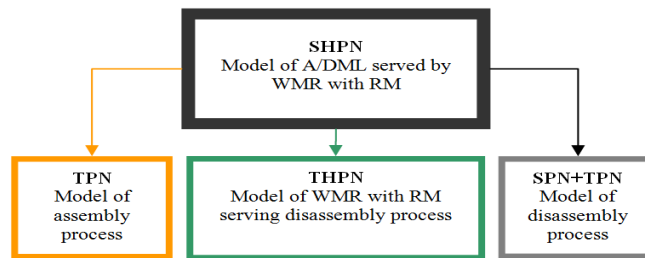
Figure 83. *Structure of the SHPN model.*

SHPN
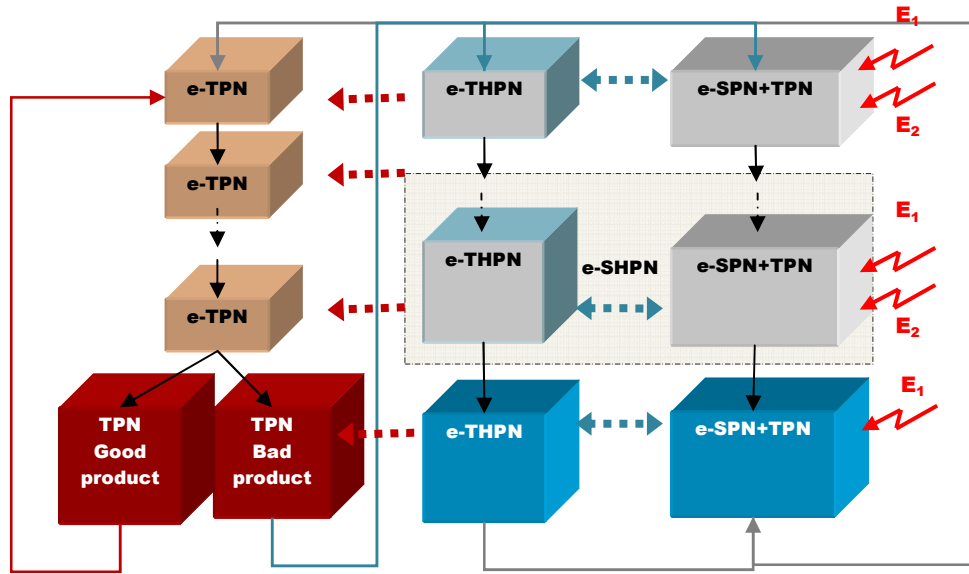
Figure 84. *SHPN representation by blocks with elementary modules: e-TPN for assembly, e-THPN for WMR with RM, e-SPN+TPN for disassembly, and e-SHPN for disassembly served by WMR with RM.*

$E_{dd(j)}^1$ and $E_{dd(j+2)}^2$ are sensor external events used for line synchronisation with the WMR equipped with RM. $E_{dd(j)}^1$ is an external synchronisation signal, corresponding to STOPPING the line and STARTING disassembly. $E_{dd(j+2)}^2$ is an external synchronisation signal, corresponding to PICKING UP the disassembled component and STARTING the line.

Simulation of SHPN model autonomously (simulation of HPN model) is useful to join the discrete dynamics of the mechatronics line with the continuous dynamics of the robotic system. Since, after the last disassembly operation, a line is no longer required to start a new disassembly, the SHPN model is different from the rest and is shown in Figure 88. SHPN model (non-autonomous HPN model), allows, in case of uncertainty (faulty sensors/actuators, poor signal reception, other faults in A/DML and robotic system), the system to stop and continue working after the fault has been removed.

7. 4. Generalised and customised SHPN model

The SHPN model (Figure 96) associated with the assembly/disassembly is a triplet

$$SHPN = \langle THPN, \quad E, \quad Sync \rangle \tag{28}$$

where:

$$\blacksquare \quad THPN = \langle P, T, Pre, Post, m_0, h, tempo \rangle \tag{29}$$

E is a set of external events

$$\blacksquare \quad E = \left\{ Edd_i^1, Edd_j^2 \right\} \cup \{e\}, i = 1 + 3 \cdot (k-1), j = 3 \cdot (k-1), k = \overline{1, N} \tag{30}$$
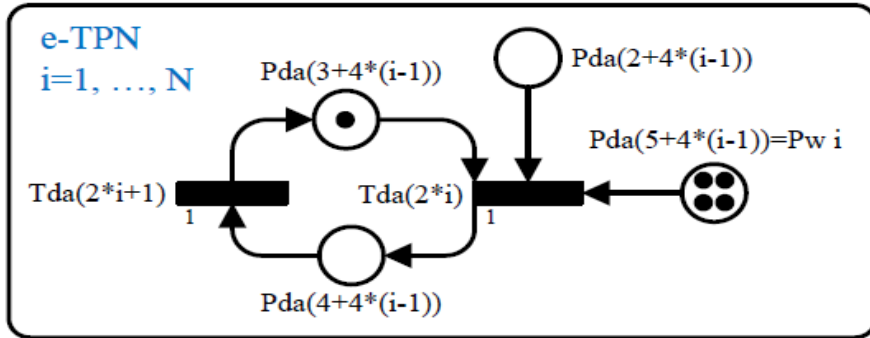
Figure 85. *e-TPN model for an elementary assembly operation.*
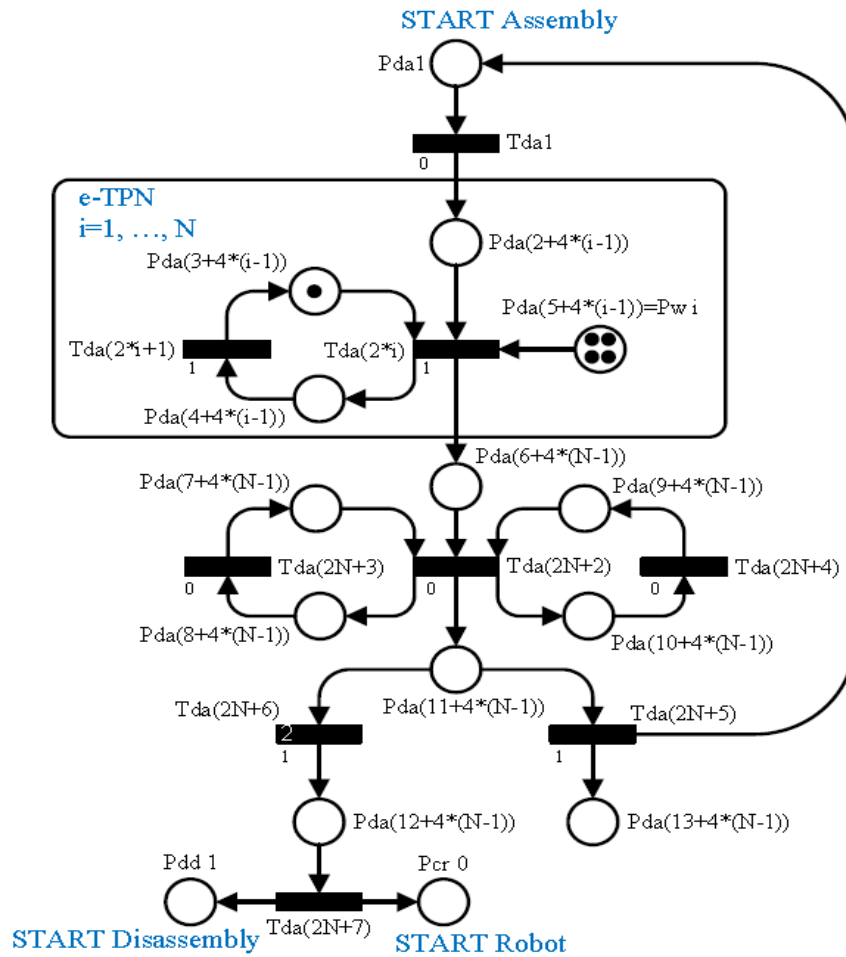
Figure 86. *Generalised TPN model for the assembly process of N components.*
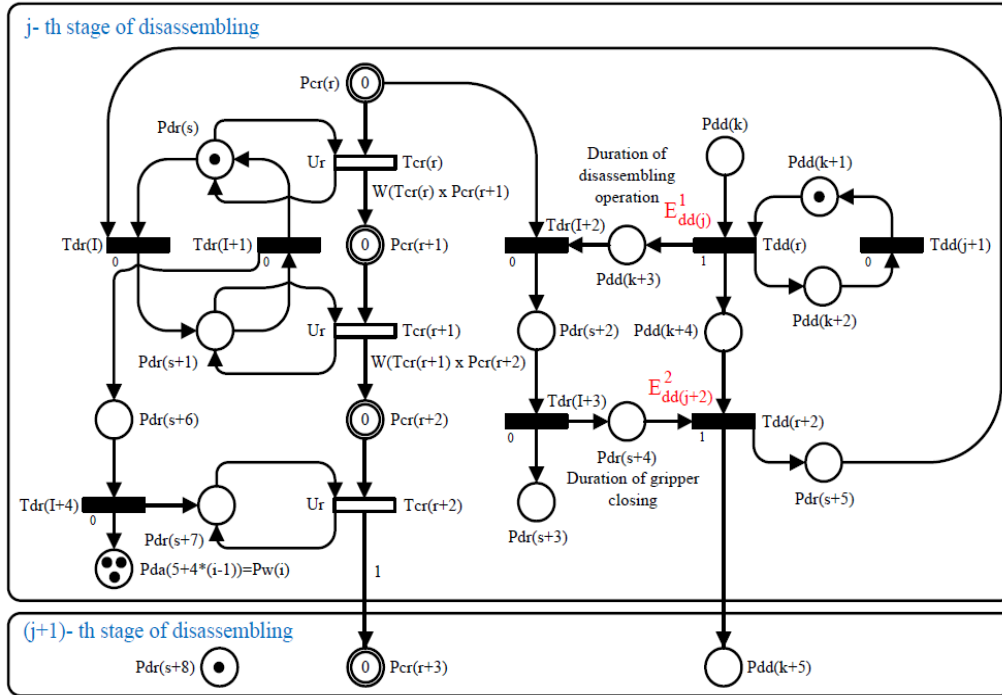
Figure 87. *e-SHPN model for the j-th elementary disassembly operation.*
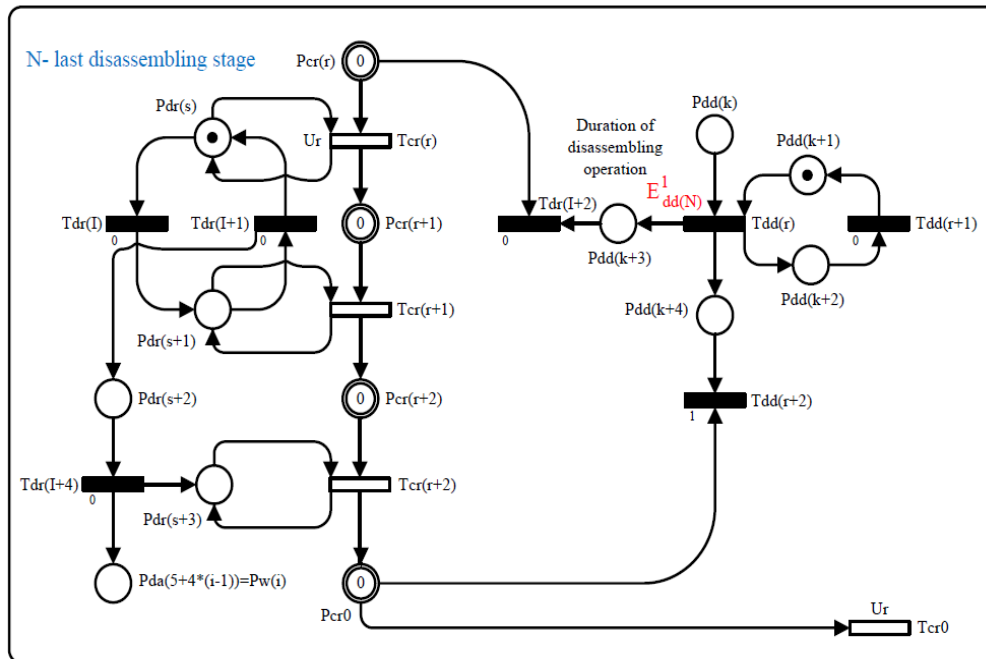
Figure 88. *SHPN model for the last disassembly operation, $j = N$.*

Sync is a function from the set of discrete disassembly transitions to the set of external events

$$Sync: T \rightarrow \left\{ E^1, E^2 \right\} \cup \left\{ e \right\},$$
(31)

where e is the continuously occurring event (it is the neutral element of the monoid E^*) and

$$Sync : \{Tdd_r\}_{r=1+3(k-1),\, k=\overline{1,N}} \rightarrow \{E^1, E^2\},$$

$$Sync : \{Tdd_i\}_{i=3(k-1),\, k=\overline{2,N}} \rightarrow \{Edd_i^2\}_{i=3(k-1),\, k=\overline{2,N}},$$

$$SyncT \setminus \{Tdd\}_{r=\overline{1,3+3(N-1)}} \cup \{Tdr\}_{l=\overline{1,4+5(N-1)}} \cup \{Tcr\}_{r=\overline{1,3+3(N-1)}} \rightarrow e$$

■ $\underline{P = \{P_1, P_2, \dots P_n\} = P^D \cup P^C}$ (32)

is a finite, not empty, set of places where P^D is the set of discrete places

$$P^D = \{Pda_i\}_{i=\overline{1,13+4(N-1)}} \cup \{Pdd_r\}_{r=\overline{1,5+5(N-1)}} \cup \{Pdr_s\}_{s=\overline{1,4+8(N-1)}},$$ (33)

and P^C the set of continuous places

$$P^C = \{Pcr_k\}_{k=\overline{0,3+3(N-1)}}.$$ (34)

— For $N = 5$ (A/DML Hera&Horstmann), (33) and (34) become:

$$P^D = \{Pda_i\}_{i=\overline{1,29}} \cup \{Pdd_j\}_{j=\overline{1,25}} \cup \{Pdr_k\}_{k=\overline{1,41}},$$

$$P^C = \{Pcr_k\}_{k=\overline{0,15}},$$

where:

$\{Pda_i\}_{i=\overline{1,29}}$ is the set of discrete places for the assembly process;

$\{Pdd_j\}_{j=\overline{1,25}}$ is the set of discrete places for the disassembly process;

$\{Pdr_k\}_{k=\overline{1,41}}$ is the set of discrete places for the mobile robot states while serving the disassembly process;

$\{Pcr_k\}_{k=\overline{1,15}}$ is the set of continuous places associated with the distances travelled by the mobile robot for each disassembly operation in order to transport the disassembled component from the disassembled location to the storage location;

■ $\underline{T = \{T_1, T_2, \dots, T_m\} = T^D \cup T^C}$ (35)

is a finite, not empty, set of transitions where T^D is the set of discrete transitions

$$T^D = \{Tda_i\}_{i=\overline{1,7+2N}} \cup \{Tdd_r\}_{r=\overline{1,3+3(N-1)}} \cup \{Tdr_l\}_{l=\overline{1,4+5(N-1)}}$$ (36)

and T^C the set of continuous transitions

$$T^C = \{Tcr_r\}_{r=\overline{1,3+3(N-1)}}$$ (37)

— For $N = 5$, (36) and (37) become

$$T^D = \{Tda_i\}_{i=\overline{1,17}} \cup \{Tdd_j\}_{j=\overline{1,15}} \cup \{Tdr_k\}_{k=\overline{1,24}},$$

$$T^C = \{Tcr_k\}_{k=\overline{1,15}},$$

where:

$\{Tda_i\}_{i=\overline{1,17}}$ is the set of discrete transitions for the assembly operation model;

$\{Tdd_j\}_{j=\overline{1,15}}$ is the set of discrete transitions for the disassembly operation model;

$\{Tdr_k\}_{k=\overline{1,24}}$ is the set of discrete transitions for the mobile robot states while serving the disassembly operations;

$\{Tcr_k\}_{k=\overline{1,15}}$ is the set of continuous transitions associated with the distances travelled by the mobile robot for each disassembly operation. The maximum linear speed of the WMR is associated with these transitions.

Remark 1:

➢   Sets P and T are disjointed, $P \cap T = \varnothing$;

➢ $Pre : P \times T \to Q_+ \ or \ N$ is the input incidence application;

➢ $Post : P \times T \to Q_+ or \ N$ is the output incidence application;

Remark 2:

➢   In the definitions of Pre, $Post$ and m_0, N corresponds to the case where $P_i \in P^D$, and Q_+ or R_+ corresponds to the case where $P_i \in P^C$.

◼ $\underline{m_0 : P \to R_+ \ or \ N}$ is the initial marking;   (38)

◼ $\underline{h : P \cup T \to \{D,C\}}$,   (39)

called "hybrid function", indicates for every node whether it is a discrete node (sets P^D and T^D) or a continuous node (sets P^C and T^C),

$$h : P^D \cup T^D \to \{D\}; \ h : P^C \cup T^C \to \{C\},$$ (40)

tempo is a function from the set T of transitions to the set of positive or zero rational numbers,

◼ $\underline{tempo : T \to Q_+ \cup \{0\}}$.   (41)

If $T_j \in T^D$, then $d_j = tempo(T_j)$ is the timing associated with T_j.

For each discrete assembly transition of the set

$$T_a^D = \{Tda_i\}_{i=2k, k=\overline{1,N}} \cup \{Tda_{2(N+1)}\},$$ (42)

$$tempo(Tda_i) = d_{da_i},$$ **(20)**

where d_{da_i} represents the duration (in seconds) associated with the corresponding assembly operation.

For each discrete disassembly transition of the set

$$T_d^D = \{Tdd_r\}_{r=1+3(k-1),\, k=\overline{1,N}},$$
(43)

d_{dd_r} is the duration of the corresponding disassembly.

For each discrete WMR transition of the set

$$T_r^D = \{Tdr_l\}_{l=4+5(k-2),\, k=\overline{2,N}},$$
(44)

d_{dr_l} is the duration of RM positioning for picking up and setting down a disassembled component.

- For $N = 5$, (19), (20), (21) and (22) become:

$$T_a^D = \{Tda_i\}_{i=\{2,4,6,8,10\}} \cup \{Tda_{12}\},$$

$$tempo(Tda_i)_{i=\{2,4,6,8,10,12\}} = \{9.5, 9.3, 8.5, 0.5, 4.75, 27.2\}$$

where d_{da_i} represents the duration of the current assembly operation together with the transport time to the next assembly location, for $i \in \{2,4,6,8,10\}$, and the duration of the quality test together with the transport time to the end product warehouse elevator, for $i \in \{12\}$;

$$T_d^D = \{Tdd_r\}_{r=\{1,4,7,10,13\}}, \quad d_{dd_r,\, r=\{1,4,7,10,13\}} = 1,$$

where d_{ddr} is the duration of the current disassembly operation,

$$T_r^D = \{Tdr_l\}_{l=\{4,9,14,19\}}, \quad d_{dr_l} \in \{5.1, 21.2, 8.9, 7.8\},$$

where d_{drl} is the duration of RM positioning for picking up and setting down a disassembled part.

If $T_{cr} \in T^C$ then

$$U_r = \frac{1}{tempo(T_{cr})}$$

is the flow rate associated with T_{cr}.

For

$$T^C = \{Tcr_r\}_{r=3+3(k-1),\, k=\overline{1,N}}, \quad U_{cr_r} = U_r;\ U_{r\max} = V_r,$$

where U_{cr} is the variable flow of the mobile robot displacement between disassembly stations. Consider the average speed of motion of WMR, $V_r = 94mm/s$.

Definition 1: The ED-enabling degree of a C-transition T_j for a marking m, denoted by $ED(T_j, m)$, is the enabling degree of T_j after all the arcs, from a $C-$ place to a $C-$ transition, have been deleted

$$ED\left(T_j, m\right) = \min_{P_i \in {}^0 T_j \cap P^D} \left\lfloor \frac{m_i}{Pre\left(P_i, T_j\right)} \right\rfloor . \tag{45}$$

Definition 2: The maximum firing speed of transition T_{cr_r} is the product of its flow rate U_r by its ED -enabling degree.

Suitable definitions 1 and 2, for the general case, can be expressed as:

$$ED\left(T_{cr_j}, m_{cr(j+1)}\right) = \{0,1\}, \tag{46}$$

$$m_{cr(j+1)} = V_j \cdot w\left(Tcr_j \times Pcr_{(j+1)}\right), \tag{47}$$

$$w\left(Tcr_r \times Pcr_{r+1}\right) = D\left(W_{N+1-j}, N_{d_{j+1}}\right) / D\left(N_{d_j}, W_{N+1-j}\right), \tag{48}$$

where $m_{cr(j+1)}$ is the mark associated with a continuous place, and $w\left(Tcr_{(r)} \times Pcr_{(r+1)}\right)$ is the weight of the arc from a continuous transition to a continuous place of the WMR.

For $N = 5$ the arches $\left(P_i \times T_j\right)$, have a weight equal to one,

Where

$$P_i = \{ROBOT\ state1, ROBOT\ state2\} \in {}^o \{Tcr_k\}_{k=\overline{1,10}} \cap P^D . $$

Remark 3:

For a synchronised PN, a transition is enabled when each of its input places contains enough tokens. If it is enabled, it is firable on occurrence of the associated event.

Sync is a function from (31), becomes in customised form as follows:

$$Sync : \left\{Tdd_j\right\}_{j=\{1,3,4,6,7,9,12,13\}} \rightarrow \left\{Edd^1, Edd^2\right\}; \tag{49}$$

$$Sync : \left\{Tdd_i\right\}_{i=\{1,4,7,13\}} \rightarrow \left\{Edd_i^1\right\}_{i=\{1,4,7,13\}} ; \tag{50}$$

$$Sync : \left\{Tdd_i\right\}_{i=\{3,6,9,12\}} \rightarrow \left\{Edd_i^2\right\}_{i=\{3,6,9,12\}} ; \tag{51}$$

$$Sync : \left\{Tdd_j\right\}_{j=\overline{1,16}} \cup \left\{Tdr_k\right\}_{k=\overline{1,21}} \cup \left\{Tcr_k\right\}_{k=\overline{1,10}} \rightarrow e . \tag{52}$$

7. 5. Simulation of the SHPN model

The proposed model, HPN, has been tested, analyzed and verified through simulation package Sirphyco. HPN model was useful to find maximum speed of the mobile platform that provides minimum cycle time of disassembly. This speed should be set respecting the physical limitations of the mobile platform, which ultimately is the optimum displacement speed. Analysis of the SHPN model is relevant at basic level according to an elementary THPN module, denoted e-THPN. The SHPN model is obtained by recurrent assembling of these elementary e-THPN modules (corresponding to each basic disassembly served by WMR with RM). The SHPN global model is an exclusive relationship between TPNs associated with the assembly process, elementary THPN modules associated with WMR service assistance, and SPN with TPNs associated with the disassembly process.

START the first stage of disassembling

Figure 89. *SHPN model of the first stage of disassembly*

Figure 91 shows the simulated response of the continuous and discrete places of WMR and RM for the hybrid model in Figure 87. The WMR markings of the continuous places, before and after simulation, match the distances shown in Figure 81. In Figure 91, the evolution of the WMR, continuous and discrete place markings, corresponding to $j = 1$, is shown as following: $Mcr(r)$ – the temporal variation of the travelled distance by the robot between stage 1 of disassembly and warehouse 5 (1031mm according to Figure 81); $Mcr(r+1)$, $Mcr(r+2)$, $Mcr(r+3)$ – the variation of the distance to be travelled by the robot in the following stage (730mm according to Figure 81) correlated to the synchronization of the events Edd_1^1 and Edd_3^2. $Mdr(s), Mdr(s+1), Mdr(s+2), Mdr(s+6), Mdr(s+7)$ – represent the temporizations associated with the discrete actions of the WMR (piece gripping and dropping, gripper closure, repositioning to the next disassembly work-station) correlated with the travelling of the disassembled piece in-between work-stations along the conveyor belt.

Figure 90. *SHPN model of the last stage of disassembly*

For the final stage of disassembly (Figure 92), the maximum value of the marking $Mcr(r+3)\big|_{j=5} = Mcr(0)\big|_{j=5}$ is equal to the distance travelled by the WMR during stage 1 of disassembly $Mcr(r) = 1031$ and corresponds to the initialization of the new disassembly cycle. Similarly, the graphic representations $Mdr(s)$, $Mdr(s+1)$, $Mdr(s+2)$, $Mdr(s+6)$, $Mdr(s+7)$ do not quantify the temporization induced by the reception of the event Edd^2 (STARTING next stage of disassembly) as the disassembly is finalized.

Pcr_(r+2)

Pcr_(r+3)

Pdr_(s)

Pdr_(s+1)

Pdr_(s+2)

Pdr_(s+6)
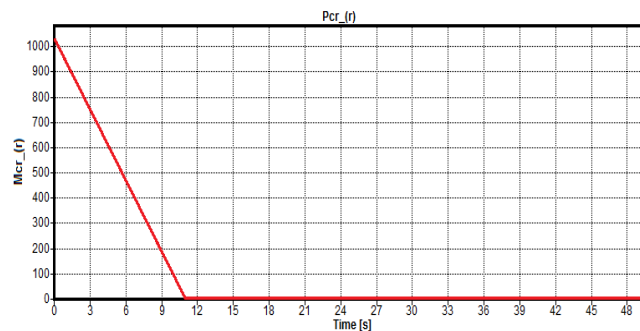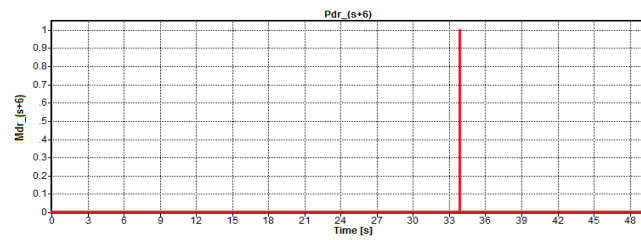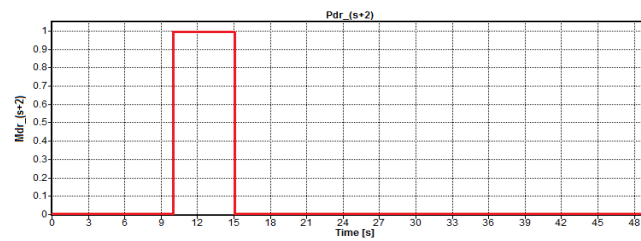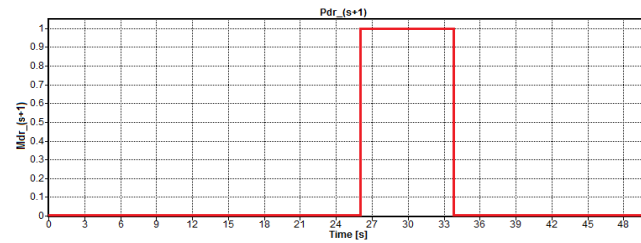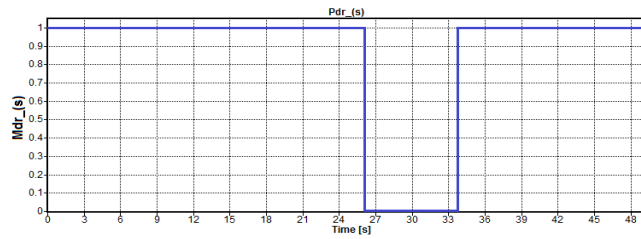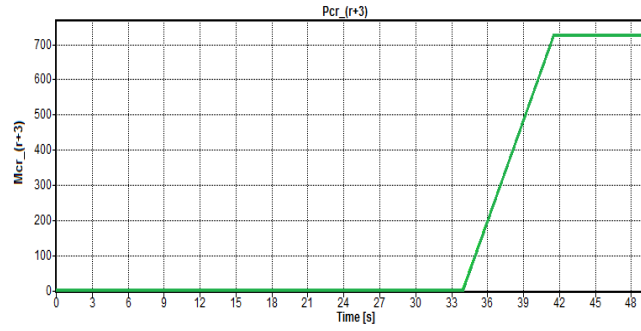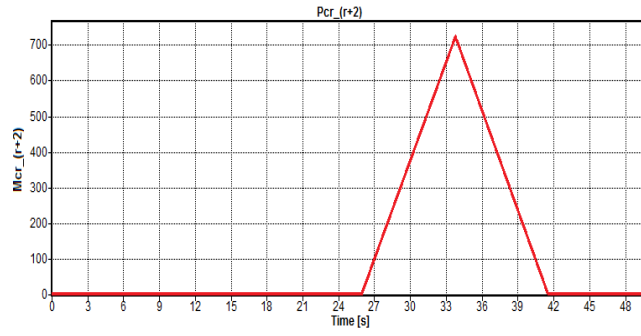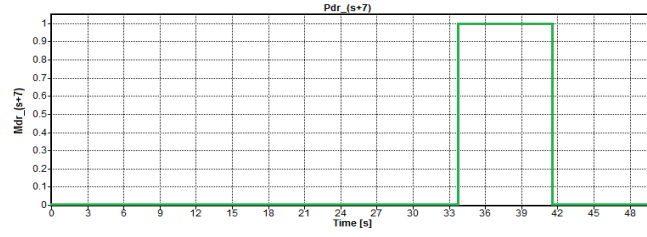
Figure 91. *Variation of the continuous and discrete places associated with displacements of WMR with RM for the first disassembly period.*
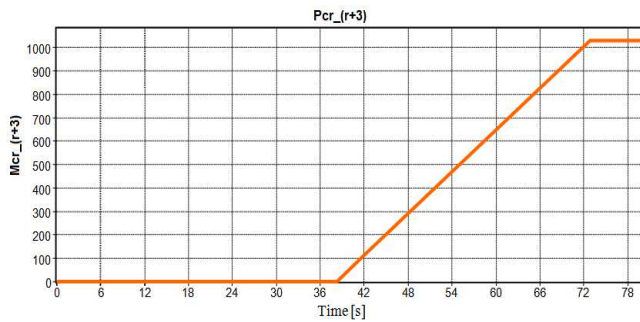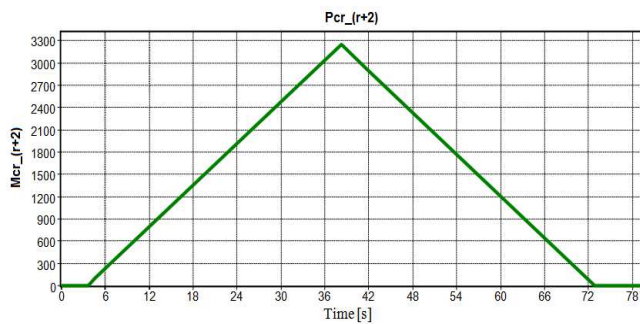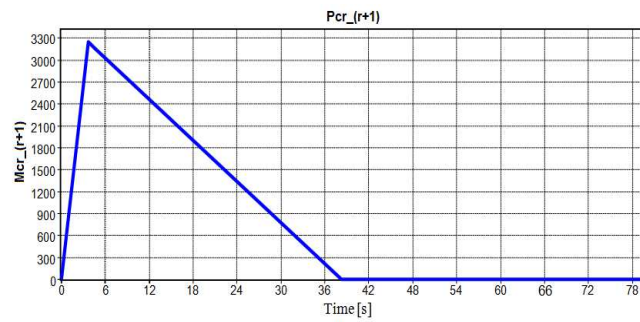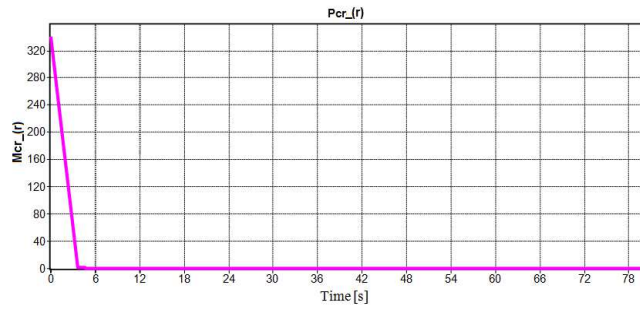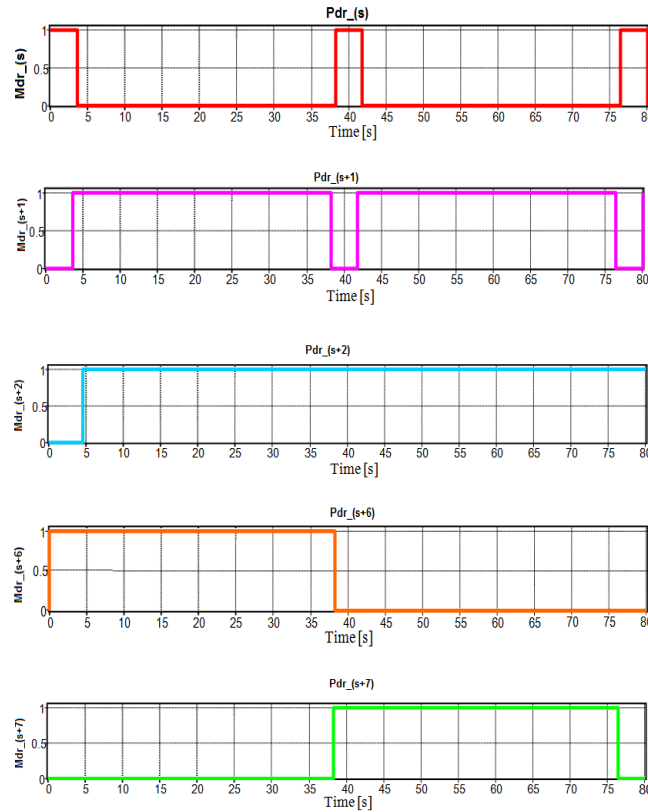
Figure 92. *Variation of the continuous and discrete places associated with displacements of WMR with RM for the last disassembly period.*

7. 6. A/DML real-time control based on A/DLB and SHPN models

The SHPN model is transposed via the LabView platform into a real-time application, obtained by interfacing the HPN model with synchronised signals taken by acquisition from the real process.
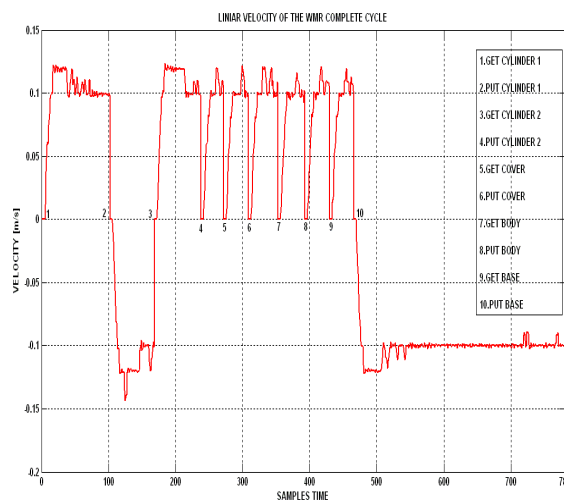
Figure 93. *WMR's linear speed during disassembly process*

The real-time application is synchronised with the controlled process by the positioning signals of the work piece along the conveyor taken by acquisition card NIUSB-6008. The synchronisation signals, used in the LabView real-time control application, validate certain transitions into the SHPN model. These transitions are conditioned by the associated signals of the position work piece on the conveyor track. Synchronisation will lead to initialising the robot and to monitoring/controlling assembly/disassembly operations of the WMR with RM. Discrete time and sliding-mode control, in trajectory tracking, based on a kinematic model, is used to control WMR ([Dum, 11]). In this way, both the robot and the flexible line are controlled, so as to achieve a minimum assembly and disassembly time cycle.
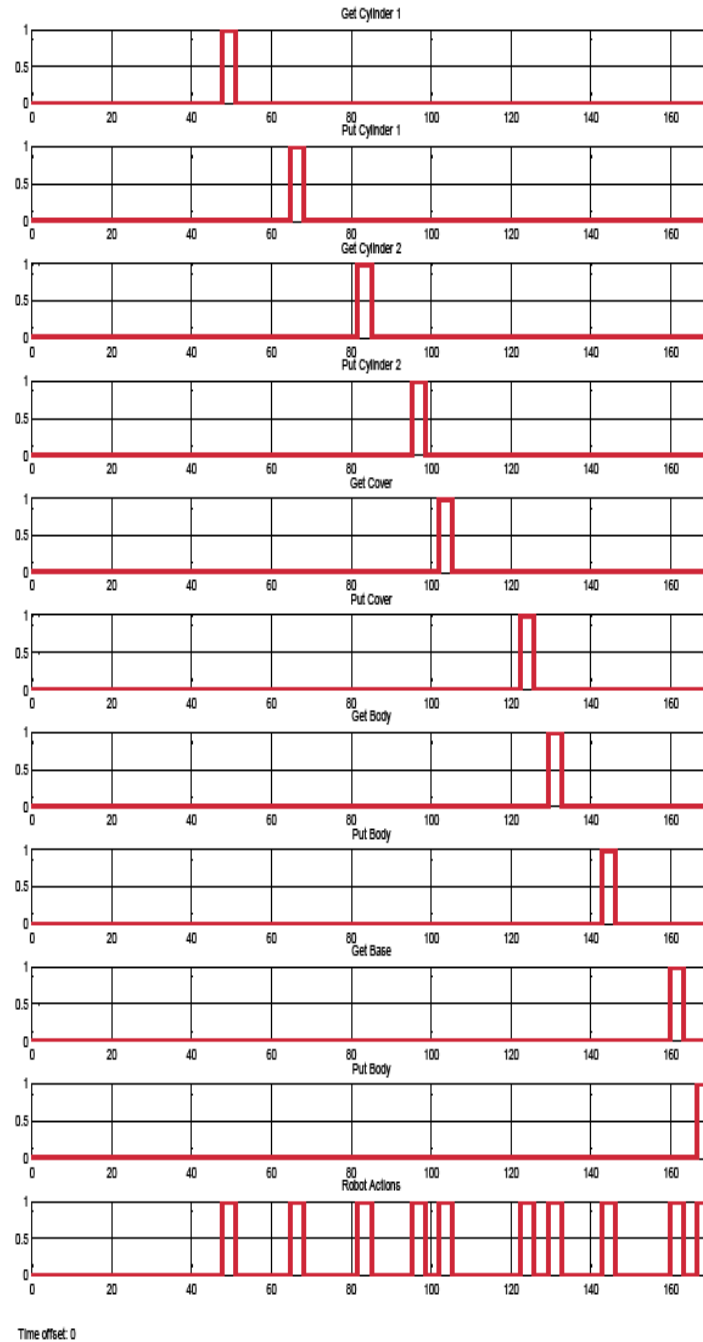
Figure 94. *State transition of disassembly parts and their transport from disassembly locations to the storage locations .*

The robot is initialised by a signal transmitted via a wireless access point mounted on the robot, received by the LabView application. Via the acquisition board, the state signals are transmitted to the flexible line to control the position of the work piece along the conveyor and to synchronise the robot with the flexible line. The LabView I/O module transmits the signals to the A/DML PLC (SIMATIC S7-300) via the acquisition board. The gripper is positioned by a visual system so as to grab the disassembled component and store it in the warehouse. Linear velocity of the complete WMR disassembly cycle in trajectory tracking, real-time, sliding-mode control, is presented in Figure 93. Sliding-mode control of the mobile platform servicing A/DML does not address issues related to the possibility of uncertainty of type: false information, faulty sensors/actuators and possible route/storage space blockage.The state transition of the disassembled components and the WMR for transport of these components to the storage location is shown in Figure 94. The complete structure of the A/DML real-time control served by WMR is shown in Figure 78.

7. 7. Generalised approach to Time Cycle Optimization for Disassembling Operations

The elementary time cycle (ETC) for the mobile robot ETC_R, corresponding for j stage of e_SHPN model, is the travel duration with constant speed between N_{d_j} - the disassembling location, W_i - the storage warehouse, $N_{d_{j+1}}$ - the next disassembling location added to durations of disassembly and manipulation operations performed by mobile robot (Figure 95):
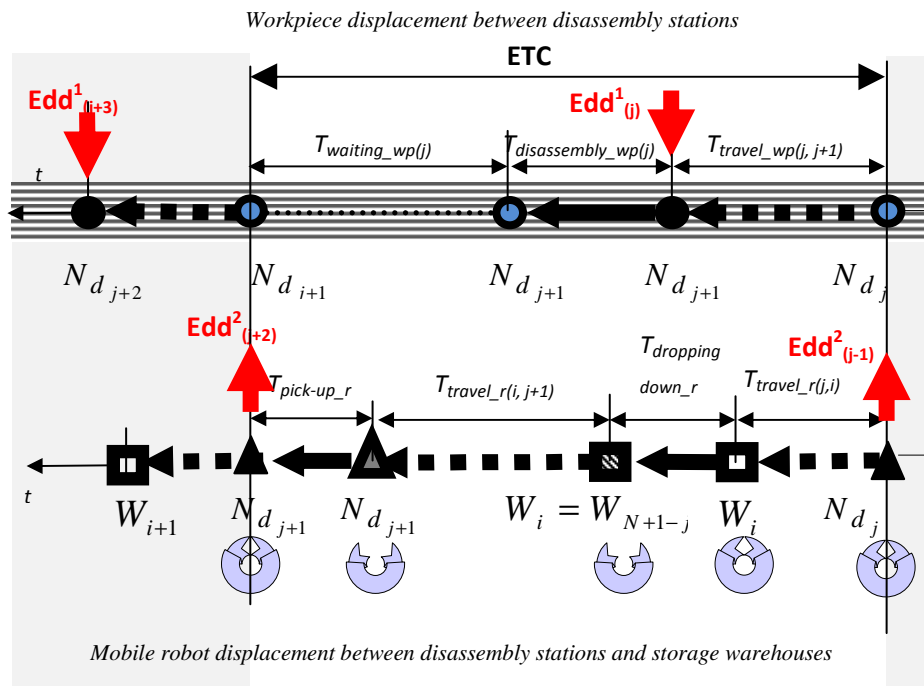
Figure 95. *Time intervals of the mobile robot and workpiece during elementary sequence of disassembly*

7.7.1. ETC calculation in mobile robot cycle approach

$$ETC = T_{travel\_r}(_{j,i}) + T_{travel\_r}(_{i,j+1})$$

where:

$T_{travel\_r}(_{j,i})$ is the travel duration between N_{d_j} - the disassembling location to W_i - the storage warehouse

$T_{travel\_r}(_{i,j+1})$ is the travel duration between W_i - the storage warehouse to $N_{d_{j+1}}$ - the next disassembling location.

$$ETC = D\big(N_{d_j}, W_{N+1-j}\big)/V_r + D\big(W_{N+1-j} + N_{d_{j+1}}\big)/V_r$$

where V_r is the mobile robot speed. From N_{d_j} station the mobile robot starts moving towards the storage warehouse after the following sequences are completed: the pick-up of disassembled components and the gripper closure. These actions of the robot are synchronised trough the synchronization signal $E_{dd_j}^2\Big|_{\substack{j=3\cdot(k-1)\\k=1,N}}$ with the start of the movement workpiece towards the next disassembly station. In e_SHPN this durations corresponds of timing associated with continous transitions T^C :

$$T_{travel\_r_j} = tempo\,(Tcr_r)\Big|_{r=3+3\cdot(j-1)} \tag{53}$$

$$T_{travel\_r_{j+1}} = tempo\,(Tcr_{r+2})\Big|_{r=3+3\cdot(j-1)} \tag{54}$$

where:

$$\{Tcr_r, Tcr_{r+2}\} \subset T^C \;,\; T^C = \{Tcr_r\}_{r=3+3\cdot(j-1)_{j=\overline{1,N}}}$$

$$m_{cr(r+1)} = V_r \cdot w(Tcr_r \times Pcr_{r+1}) = V_r \cdot w_r \tag{55}$$

$$m_{cr(r+2)} = V_r \cdot w(Tcr_{r+1} \times Pcr_{r+2}) = V_r \cdot w_{r+1} \tag{56}$$

and $w_r = (Tcr_{r-1} \times Pcr_r)\Big|_{r=1+3\cdot(j-1)_{j=\overline{1,N}}}$

$$\begin{cases} w_r = D\big(W_{N+1-j}, N_{d_{j+1}}\big)/D\big(N_{d_j}, W_{N+1-j}\big) \\ w_{r+1} = D\big(N_{d_{j+1}}, W_{N-j}\big)/D\big(W_{N+1-j}, N_{d_{j+1}}\big) \end{cases} \tag{57}$$

The durations of picking-up and dropping-down the disassembled components corresponds of manipulation actions for the j stage. In e_SHPN this durations corresponds of timing associated with discrets transitions:

$$T^D = \{Tda_i\}_{i=\overline{1,7+2\cdot N}} \cup \{Tdd_r\}_{r=\overline{1,3+3\cdot(N-1)}} \cup \{Tdr_l\}_{l=\overline{1,4+5\cdot(N-1)}}$$

$$T_{pick-up\_r_j} = d_{dr_{l+2}}\Big|_{\substack{l=1+(j-1)\cdot4\\j=1,N}} = d_{dr_{3+(j-1)\cdot4}}\Big|_{j=\overline{1,N}} \tag{58}$$

$$T_{dropping\_down\_r_j} = d_{dr_{l+3}}\Big|_{\substack{l=1+(j-1)\cdot 4 \\ j=1,N}} = d_{dr_{4+(j-1)\cdot 4}}\Big|_{j=\overline{1,N}} \tag{59}$$

$l = 1+(j-1)\cdot 4$ - indexes a discrete place of the robot states.

The time cycle duration and its components can be identified within the temporal marking evolution corresponding to j stage of SHPN model. In this case the ETC for the mobile robot- ETC_R corresponding to j stage, are:

$$\begin{aligned} ETC_{R_j} &= T_{travel\_r_j} + T_{travel\_r_{j+1}} + \\ &\quad T_{pick-up\_r_j} + T_{dropping\_down\_r_j} \end{aligned} \tag{60}$$

$$\begin{aligned} ETC_{R_j} &= D\big(N_{d_j}, W_{N+1-j}\big)/V_r + \\ &\quad D\big(W_{N+1-j}, N_{d_{j+1}}\big)/V_r + \\ &\quad d_{dr_{3+(j-1)\cdot 4}} + d_{dr_{3+(j-1)\cdot 4}}\Big|_{j=\overline{1,N}} \end{aligned} \tag{61}$$

7.7.2. ETC calculation in workpiece cycle approach

The workpiece makes successive travels between disassembly stations. The actions STOP / START line disassembly, or START disassembly / picking up of disassembled component are triggered by external synchronization signals $E^1_{dd(j)}$ is an external synchronization signal, corresponding to STOPPING line and STARTING disassembly. $E^2_{dd(j+2)}$ is an external synchronization signals, corresponding to PICKING UP of disassembled component and STARTING line.

$T_{travel\_wp_{j,j+1}}$ is the travel duration workpiece between N_{d_j} - the disassembling location to $N_{d_{j+1}}$ - the next disassembling location. $T_{disassembly\_wp_j}$ is the duration of disassembly operation for j stage. The commands START disassembly is launched after the $E^1_{dd(j)}$ sychronisation signal reception. During $T_{waiting\_wp_j}$ the workpiece expected the end of pick-up action performed by the mobile robot. In this case the elementary time cycle in the workpiece approach ETC_{WP} is:

$$\begin{aligned} ETC_{WP_j} &= T_{travel\_wp_{j,j+1}} + \\ &\quad T_{disassembly\_wp_j} + T_{waiting\_wp_j} \end{aligned} \tag{62}$$

$$\begin{aligned} ETC_{WP_j} &= d_{dd_r}\Big|_{r=1+(j-1)\cdot 3} + d_{dd_{r+2}}\Big|_{r=1+(j-1)\cdot 3} + \\ &\quad T_{waiting\_wp_j} \end{aligned} \tag{63}$$

The optimization of time cycle (*TC*) for the mobile robot approach implies the minimization of disassembly operations duration (if possible) and the minimization of manipulation durations. Optimal value for the optimal cycle time (*TCO*) becomes:

$$TC = \sum_{j=1,N-1} ETC_{R_j} = \sum_{j=1,N-1} ETC_{WP_j} \tag{64}$$

$$TCO = \min \sum_{j=1,N-1} ETC_{R_j} \geq \min \sum_{j=1,N-1} ETC_{WP_j} \tag{65}$$

$$
\begin{aligned}
TCO \;=\; & \sum_{j=1}^{N-1} D\left(N_{d_j}, W_{N+1-j}\right)/V_{r\_opt_j} \\
& + \min \sum_r \left(d_{dr_{3+(j-1)\cdot4}} + d_{dr_{3+(j-1)\cdot4}}\right)\Big|_{j=\overline{1,N}} \\
& + \sum_{j=1}^{N-1} D\left(W_{N+1-j}, N_{d_{j+1}}\right)/V_{r\_opt_j}
\end{aligned}
\tag{66}
$$

At the same time it must be provided the temporal synchronization between $\min\left(ETC_{R_j}\right)$ and $\min\left(ETC_{WP_j}\right)$ for each j stage. For the SHPN model this restriction is equivalent to avoid the blockage for PN model:

$$
\begin{aligned}
\min\left(ETC_{R_j}\right) =\; & D\left(N_{d_j}, W_{N+1-j}\right)/V_r + \\
& D\left(W_{N+1-j}, N_{d_{j+1}}\right)/V_r + \\
& \min\left(d_{dr_{3+(j-1)\cdot4}} + d_{dr_{3+(j-1)\cdot4}}\right)
\end{aligned}
\tag{67}
$$

$$\min\left(ETC_{WP_j}\right) = d_{dd_r}\Big|_{r=1+(j-1)\cdot3} + d_{dd_{r+2}}\Big|_{r=1+(j-1)\cdot3} \tag{68}$$

$$\min\left(ETC_{R_j}\right) = \min\left(ETC_{WP_j}\right) \Rightarrow V_{r\_optimum_j} \tag{69}$$

$$V_{r\_opt_j} = \frac{d_{dd_{j-2}} + d_{dd_j} - \min\left(d_{dr_{3+(j-1)\cdot4}} + d_{dr_{3+(j-1)\cdot4}}\right)}{D\left(N_{d_j}, W_{N+1-j}\right) + D\left(W_{N+1-j}, N_{d_{j+1}}\right)} \tag{70}$$

$$V_{RO} = \min\left\{V_{r\_opt_j}\right\}_{j=\overline{1,N}} \tag{71}$$

$$
\begin{aligned}
TCO \;=\; & \sum_{j=1}^{N-1} D\left(N_{d_j}, W_{N+1-j}\right)/V_{RO} \\
& + \min \sum_r \left(d_{dr_{3+(j-1)\cdot4}} + d_{dr_{3+(j-1)\cdot4}}\right)\Big|_{j=\overline{1,N}} \\
& + \sum_{j=1}^{N-1} D\left(W_{N+1-j}, N_{d_{j+1}}\right)/V_{RO}
\end{aligned}
\tag{72}
$$
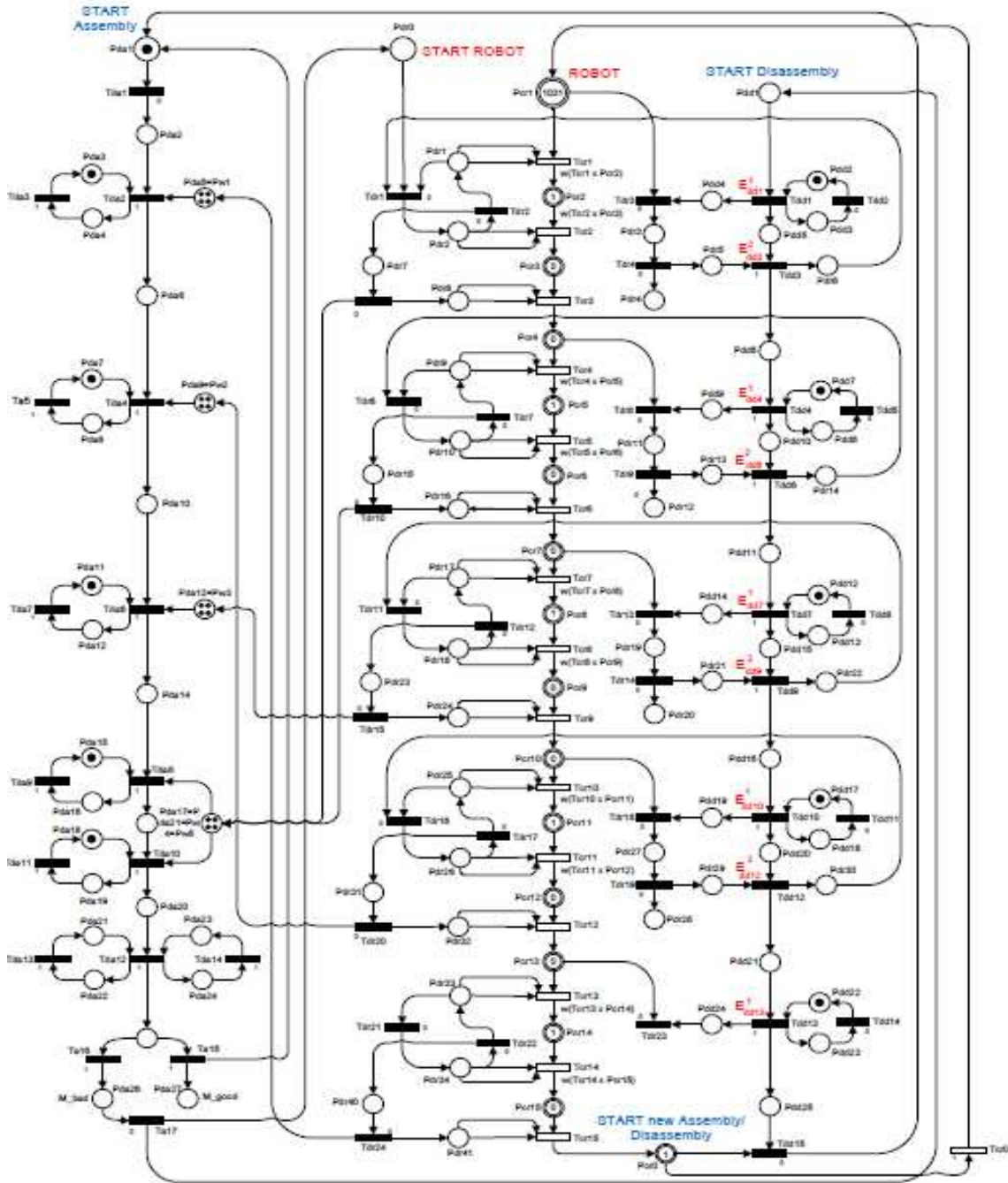
Figure 96. *SHPN model cooresponding of reversible assembly/disassembly manufacturing line (A/DML) served by wheeled mobile robot (WMR) equipped with robotic manipulator (RM), composed by 5 workstations*

Conclusions

This researchs are mainly focused on operations planning and control of an A/DML served by a mobile platform equipped with manipulator. Real-time control of a fully reversible A/DML served by WMR equipped with RM is based on operations planning and SHPN model, via a LabView platform. The A/DLB and the generalised SHPN models are customised for an A/DML assembling a five-part product. The SHPN model is conditioned on certain state transitions by external events representing signals supplied by sensors. The WMR equipped with RM is used only during disassembly for transporting the disassembled parts to the storage warehouses. A disassembly process is started when the final product, obtained by assembly, is

damaged. The disassembled components are recovered and transported to storage locations, in order to be used again in the assembly process. The SHPN model has been tested via simulation, and used in real-time control.

The problem needs to be solved in the future is robustness to uncertainties of the mechatronics line and robotic platform. Have to be considered as uncertainties: faulty sensors/actuators, route/storage space blockage and payload variation. Also, need to be used collaborative systems of mobile platforms equipped with manipulators to transport and handle weights in a wide range of variation.

The most eloquent correspondents in the real world are assembly processes in the automotive industry, car body, gearbox and engine block assembly. In most cases, robotic manipulators that have a fixed location serve these assembly lines. Through this study, we extended the degree of automation and efficiency of these production lines using mobile robotic systems equipped with manipulators. Thus, the assembly lines become reverse, being able to recover and reuse of components and subassemblies, in the event that the final product does not meet quality requirements.

Chapter 8

Evolution and Development of Academic Career

Taking into consideration the research and teaching activities performed so far, I believe that I can outline a personal development strategy that will allow me to advance in many domains of scientific and academic interest.

On a short term, I wish to build a research team that has important competencies in the modeling and control of automatic systems. This team will have to articulate their activity to the multi-disciplinary collectives within ICSTM (The institute for Multidisciplinary Scientific and Technological Research) of UVT, so that we may reach significant achievements in applied laboratory and industrial research. On a long term, I believe that there is a value potential for developing concepts in the domain research, so that we may reach significant scientific results in fundamental research.

Such an approach will allow this research group's paticipation in national and European competitions, with consistent research projects proposals. Also on a long term, I anticipate the possibility of reactivating international collaboration relations, which the automatics specialists group within the AIIE Department has had for years with engineering universities and schools in Europe, on research directions in Systems Engineering.

In order to detail my personal career development strategy, I shall continue this report as follows:

> 1. Scientific activity
>   1.1. Targeted domains and previous scientific contributions
>   1.2. Objectives planned for subsequent development
> 2. Didactic activity
>   2.1. Didactic experience accumulated so far
>   2.2. Development plan for educational activities

1. Scientific activity

1.1. Targeted domains and previous scientific contributions

MAINTENANCE AND E-MAINTENANCE ENGINEERING

> The context of the research activity: *Doctorate scholarship in cotutelle. Laboratoire d'Automatique de Besançon (UMR CNRS 6596), UNIVERSITE de Franche-Comté, Spécialité: Automatique et Informatique, 2005*

- Implementation of a dynamic monitoring system based on Fuzzy Petri Nets (*MFPN*). The model was built with Fuzzy Petri Nets for Monitoring (*MFPN*), an original tool whose definition derives from the general category of Fuzzy Petri Nets. The principle of this tool lies in the transformation of the faults tree (FT) into a PN-type structure, with the integration of the fuzzy marking concept. The fuzzy marking derives from the fuzzy rules associated to faults propagation. This *MFPN* customised on FT modelling becomes a dynamic monitoring tool, capable – through the fuzzy marking evolution, to anticipate the occurrence of a fault before the instauration of an effective critical state.

- Implementation under the platform Labview of a real-time client-server monitoring platform, based on the monitoring tool defined with *MFPN*. The tool was implemented in the websites of Valahia University in Targoviste and LAB Besancon. At the Valahia University, a distance monitoring system was activated, whereas at LAB Besancon we installed the client module for real-time acquisition of information that describe faults occurrence.

- The conceptual definition of a new tool destined for the recurrent refinement of information. Recurrent Synchronized Petri Nets - *RecSinFPN* represents an extension of the *MFPN* proposal and is derived from the necessity of monitoring function refining. The recurrent aspect brings more precision to the model associated with the monitoring function, if the tool is customised for the monitoring function modelling. *RecSinFPN* is based on hierarchical and distributed structure. A distributed system's hierarchical structure may describe causal interdependencies. In the case of detection and diagnosis, the *RecSinFPN* tool is applied for a critical faulty state's location, while specifying its occurrence probability. The recurrent aspect of *RecSinFPN* is reflected in the model's capability to evolve on hierarchical levels, maintaining at each commutation the state information from the previous level.

- The conceptual definition of a new tool destined for the correction of the monitored system's degraded states. The correction mechanism is modeled by another specialized PN tool, built on the same fuzzy approach principles. The degraded states recovery/repair model was built with a dedicated tool: *Recovery Fuzzy Petri Nets* (*fr*: *Réseau de Petri Flou pour la Maintenance)* (*RFPN*) that models a fuzzy expert system. The proposed *RFPN* tool preserves the fuzzy temporal aspect by the real-time information exchange with the monitoring system's model. It functions in double interface with the monitoring function's model (*MFPN*) and the process' model (*TOOPN*) through synchronization signals. In the development of this new tool, the following entities were used: input variables – « Symptoms » of possible faults and fuzzy rules concepts. They describe the dependence between causes (occurred faults) and the effects of their occurrence. The transitions of *RFPN* model materialize the generalized modus ponens operator, which is situated at the base of the composition between inputs and the logical rules concepts.

- The conceptual definition of the global fuzzy control model. It has the consistency of a hybrid system, due to the different typology of signals interfaced with models (synchronization signals associated with fuzzy values in different object-oriented definition structures) as well as to the different typology of models (*MFPN*, *RFPN*, *TOOPN*). The information in the models' interface are transferred through emission/reception signals, the communication system being built on the Petri nets model with internal synchronizations. For each tool, an interface mechanism was conceived, which makes the implementation of the *Control-Process-Monitoring-Decision* loop possible.

Representative publications in connection with the research direction:

- **Minca E.**, Racoceanu D., Zerhouni N., *Monitoring systems modeling and analysis using fuzzy Petri nets*, Studies in Informatics and Control Journal

magazine, SIC vol.11, nr.4, edited by ICI Bucharest, **ISSN** 1220-1766, **2002**

- **Minca E.**, Dragomir O., Dragomir F., Enache A., *Temporal Recurrent Modeling Applied to Manufacturing Flexible Lines Served by Collaborative Robots*, Pg. 749 - 754, 8th Asian Control Conference ASCC2011, Proceedings of the 8th Asian Control Conference, **Conference Location :** Kaohsiung, **E-ISBN:** 978-89-956056-4-6, **Print ISBN:** 978-1-61284-487-9, **ASCC 2011**

- **Minca E.**, Dragomir O., Dragomir F, *Improvement of recurrent fuzzy detection/diagnostic functions modeling. A temporal modeling application for fault states in a manufacturing system*, 2010 8th IEEE International Conference on Control and Automation (ICCA), Pg. 1456 – 1461, **Conference Location :** Xiamen, China, **ISSN :** 1948-3449, **Print ISBN:** 978-1-4244-5195-1, **Digital Object Identifier:** 10.1109/ICCA.2010.5524311, **Issue Date:** 9-11 June 2010; **ICCA 2010**

- **Minca E.**, Zemouri R., Dragomir F., Dragomir O., *Hierarchical Monitoring Systems using recurrent synchronized fuzzy Petri Nets*, European Control Conference, ECC'09, Budapest, Hungary, pg.4775-4779, **ISBN** 978-963-311-0, 2009, Hungary, **ECC 2009**

THE MODELING AND CONTROL OF FABRICATION SYSTEMS SERVED BY MOBILE ROBOTS EQUIPPED WITH MANIPULATORS

The context of the research activity: *PN-II-ID-PCE-2011-3-0641,* « *Advanced control of reversible assembly/disassembly manufacturing systems using wheeled mobile robots equipped with robotic manipulators* » (2011 – 2014)

- The theme of fabrication systems served by collaborative robots modeling is extended to the research performed towards the elaboration of the *generalized model for fabrication systems destined for repetitive actions*, with particularization on assembly/disassembly actions. The model associated to these systems is created through specialized *SHPN*-type tools. The generalized model, as well as an optimization analysis of the cycle time, are particularized on a laboratory manufacturing system, for which we created the real-time control platform. The *SHPN* model associated with the control of the mechatronic system destined for assembly/disassembly, served by collaborative robots, is at the base of the real-time control strategy of the process, implemented under the platform LabView.

- The elaboration of the SHPN model built with Hybrid Petri Nets, associated with the automatic control of a *reversible* mechatronic line. The *SHPN* model describes the succession of assembly/disassembly operations performed on a mechatronic line, controlled with the synchronization signals of the mobile platform's movement in relation with certain sequences and reference points of workstations. The hybrid structure of the *SHPN* model results from the modeling of the mechatronic line's discrete dynamic, but also of the continuous variation dynamic of the mobile platform's position. By using these *SHPN*-type models, a real-time control structure was implemented under the platform Labview, a structure that would automate the reversibility of the assembly/disassembly line served by a mobile platform equipped with a manipulator.

Representative publications in connection with the research direction:

- **Eugenia Minca**, Adrian Filipescu, Alina Voda*, Modeling and control of an assembly/disassembly mechatronics line served by mobile robot with manipulator*, Control Engineering Practice, Volume 31, October 2014, Pages 50–62, Elsevier Publishing House.

- **Minca, E**., *A New Approach for the Control Optimization of an Assembly/Disassembly Mechatronics Line Served by an Autonomous Robotic System*, STUDIES IN INFORMATICS AND CONTROL, Volume: 23, Issue: 1, Pages: 13-22, Published: MAR 2014, ISSN: 1220-1766, Accession Number: WOS:000333661500002

- **Minca, E**(Minca, Eugenia), *A Theoretical Approach of the Time Cycle Optimisation Based Control of a Mechatronics Line Served by Mobile Robot*, MECHATRONICS AND INDUSTRIAL INFORMATICS, PTS 1-4 Book Series: Applied Mechanics and Materials Volume: 321-324 Pages: 1666-1669, Published: 2013, WOS:000324348201027, International Conference on Mechatronics and Industrial Informatics (ICMII 2013), MAR 13-14, 2013, ISSN: 1660-9336, ISBN: 978-3-03785-694-9, **ICMII2013**

- **Minca, E**(Minca, Eugenia); Voda, A (Voda, Alina); Filipescu, A (Filipescu, Adrian); Filipescu, A (Filipescu, Adriana, Jr.), *Hybrid Model Based Control of a Mechatronics Line Served by Mobile Robot with Manipulator*, PROCEEDINGS OF THE 2013 IEEE 8TH CONFERENCE ON INDUSTRIAL ELECTRONICS AND APPLICATIONS (ICIEA) Book Series: IEEE Conference on Industrial Electronics and Applications Pages: 1296-1301, WOS:000326679200237, JUN 19-21, 2013, Melbourne, AUSTRALIA, ISBN: 978-1-4673-6322-8, **ICIEA2013**

- **E. Minca,** A. Filipescu and A. Voda, New *Approach in Control of Assembly/Disassembly Line Served by Robotic Manipulator Mounted on Mobile Platform*, Proceedings of The 2012 IEEE International Conference on Robotics and Biomimetics (ROBIO 2012), 978-1-4673-2126-6/12/$31.00 © 2012 IEEE, **ROBIO 2012**

INTELLIGENT MODELING OF RENEWABLE ENERGY PRODUCTION/CONSUMPTION DYNAMICS WITH PETRI NETS

> The context of the research activity: *PNCDI2-PARTNERSHIPS-21015/2007* « *Romania's contributions to European targets regarding the development of renewable energy sources (PROMES)* »

- The modeling with Petri Nets of decisional dynamics for a renewable energy production-consumption autonomous system. This approach has imposed the conceptual definition of a distributed hierarchic system which describes the dynamics of the corresponding system to certain temporal monitoring windows.

- The modeling with Recurrent Synchronized Fuzzy Petri Nets (*RecSinFPN*) of renewable energy production/consumption hierarchical systems. The modeling tool *PNSinFREC* allowed the modeling of subsystems, qualitatively and quantitatively differentiated under the aspect of renewable energy production/consumption, but integrated into a distributed hierarchical structure system. For these reasons, the *RecSinFPN* tool integrates Object-oriented PNs in its definition (*OOPN*).

Representative publications in connection with the research direction:
- **Minca, Eugenia**; Dragomir, Otilia Elena; Dragomir, Florin, *Producer-Consumer Distributed Energy Production Systems modeling with a new Approach of Recurrent Synchronized Fuzzy Petri Nets*, Book Group Author(s): IEEE, Conference: 8th World Congress on Intelligent Control and Automation

(WCICA) Location: Jinan, Date: JUL 06-09, **2010,** Sponsor(s): IEEE , Source: 2010 8TH WORLD CONGRESS ON INTELLIGENT CONTROL AND AUTOMATION (WCICA) Pages: 1668-1673 DOI: 10.1109/WCICA.2010.5554783 , **WCICA 2010**

▪ **Minca E**, Filip F, Racoceanu D, Stefan V, Stefan A, *Advanced methods for recurrent hierarchical systems modeling. Application to producer-consumer distributed energy production system*s, Book Group Author(s): IEEE, Conference: 7th Asian Control Conference (ASCC 2009), Hong Kong, Date: AUG 27-29, 2009 , VOLS 1-3 Pages: 1542-1547 Published: 2009, **ASCC 2009**

1.2. Objectives planned for subsequent development

Subsequent scientific research will firstly target complementarity aspects in relation to the research directions presented previously.

In the research direction « Maintenance and e-maintenance engineering » the plan is to implement the proposed modeling tools, especially the supervisor tool, in a laboratory application. By analyzing previous research from the point of view of the obtained results, I believe that a part of the previous research is situated in the area of theoretical definitions, of model and simulation elaboration proposals, without being tested through real-time process control applications. I believe that the activity within the partnership research project « *Prototypes of autonomous robotic systems destined for medical-social assistance and serving fabrication processes in metallurgy, ceramics, glass and automobile industry* », PN-II-PT-PCCA-2013-4-0686 (2014-2016) » will allow the acquisition of equipments which will be able to constitute a manufacturing system served by mobile platforms equipped with manipulators. The construction of this new research laboratory will allow the work team to develop new research directions in the domain of systems engineering but also the testing of previous theoretical proposals.

Thus, through the realization plan of this project, we will develop a robotic platform prototype based on a robotic system with two motor wheels and one or two free wheels, (2DW/1FW, 2DW/2FW), equipped with a robotic manipulator with 6 degrees of freedom (6-DOF). Through the modeling operation, the autonomous robotic system will be associated with kinematic and dynamic models for which we will project advanced control algorithms specific to non-linear systems (sliding-mode and backstepping). These algorithms will ensure robustness in parametrical and model disturbances and uncertainties. The prototype will be equipped with robotic manipulators with 6 degrees of freedom, for which we will project and implement control systems based both on the kinematic model and on the dynamic model. For a precise positioning, a visual serving system will be projected and implemented.

Autonomous robotic systems equipped with robotic manipulators will serve flexible assembly/disassembly mechatronic lines in order to make them reversible, i.e. capable of also performing disassembly, respectively reprocessing. For robotic systems, we will elaborate control algorithms in a collaborative approach, which represents the implementation of previously developed theoretical concepts. Also, we will elaborate the Hybrid Petri Nets models (*HPN*) of two mechatronics lines, one assembly/disassembly line (Hera&Horstmann) and one processing/reprocessing line (Festo), served by autonomous robotic systems, respectively mobile robots (2DW/1FW) and 2DW/2FW) equipped with 6-DOF manipulators. We intend to elaborate a generalized HPN-type model, for two fabrication lines served by collaborative robotic systems. This model will constitute the theoretical support in projecting and implementing a control system that responds to task balancing concepts, with the purpose of optimizing fabrication and avoiding blockages.

The continuance of research within the project PN-II-ID-PCE-2011-3-0641, « *Advanced control of reversible manufacturing systems of assembling and disassembling using wheeled mobile robots equipped with robotic manipulators* » (2011 – 2015) will allow the development of theoretical fundaments for reversible assembly lines control: the fabrication process monitoring by applying the recurrent synchronized modeling concept, the balancing of fabrication fluxes by elaborating an optimal planning strategy for workstations; the advanced control of mobile robotic systems for the precise movement on a certain trajectory, in variable task conditions but In determined temporal windows, the fabrication planning correlated with the dynamic control of waiting queues; the collaborative robotic system's control as an autonomous continuous non-linear system. The hybrid system will be structured on two subsystems: the control system of fabrication lines and the continuous system associated with advanced control structures that ensure the robustness of the collaborative transport system's functioning.

2. Didactic activity

2.1. Didactic experience accumulated so far

The teaching activity was addressed during the entire period 1996-present, to the students of the *Electrical Engineering, Electronics and Information Technology Faculty*.

In 1996-1997, as titular assistant, I presented practical papers and seminaries on themes related strictly to the domain of informatics fundamental concepts. It was an interesting stage, because it confronted me with a new profession but also with the decision whether to continue on this path.

In 1997-2004, as lecturer, I prepared the first courses, as well as laboratory projects and seminaries. Having a mechanical formation by the nature of the bachelor degree education, I sustained course and laboratory activities, especially in the Mechatronics and Electromechanics specializations.

In parallel, due to my doctorate research activity, I succeeded in remaking a specialty engineering construction that later allowed me to perform my teaching activity within the Automatics and Applied Information specialization. My doctorate research in LAB Besancon (2000-2005) was an exceptional experience both from the point of view of approached research domains, and of the assimilation and detailing in another manner of the academic teaching profession's culture. For these reasons, starting with 2004, the year I passed my teaching degree exam for Associate Professor, I managed to begin activities in the domain of Systems Engineering.

2.1.1. Structure of the didactic activity before the implementation of the LMD system (Bologna)

My didactic activity before the implementation of the Bologna system (2008) consisted of teaching activities in the following disciplines, courses and laboratories/seminaries:

- Control Engineering
  - o Undergraduate cycle: Automatics and Applied Informatics, FIE-UVT
- Automatic control techniques
  - o Undergraduate cycle: Industrial energetic, FIE-UVT
- Systems Theory and Control Engineering
  - o Undergraduate cycle: General electrotechnics, FIE-UVT
  - o Optimal and adaptive systems: Automatics and Applied Informatics, FIE-UVT

- Optimal and adaptive systems:
  - o Undergraduate cycle : Automatics and Applied Informatics, FIE-UVT
- Computer aided design
  - o Undergraduate cycle : Automatics and Applied Informatics, FIE-UVT
  - o Undergraduate cycle: Calculation technique
- Introduction to using computers
  - o Undergraduate cycle: Applied Electronics
- Introduction to Economic Informatics
  - o Undergraduate cycle: Bookkeeping Informatics College

2.1.2. Structure of the didactic activity after the implementation of the LMD system

After the year 2008, along with the transition to the Bologna system, the previous didactic activities were supplemented with those performed within the master degree programs of FIE-UVT, as follows:

- General manufacturing
  - o Master degree cycle: Industrial Production and Informatics
  - o Master degree cycle: Advanced Productive Automatics and Industrial Informatics
- Advanced modeling and simulation techniques DES
  - o Master degree cycle: Advanced Productive Automatics and Industrial Informatics
- Dynamic systems modeling with discrete events
  - o Master degree cycle: Electronics and Telecommunications

Beginning with the academic year 2014-2015, I am preparing the new course for the AII specialization:
- Discrete events systems
  - o Undergraduate cycle: Automatics and Applied Informatics
- Complex systems control strategies
  - o Master degree: Advanced Productive Automatics and Industrial Informatics

2.2. Development plan for educational activities

I believe that the development of one's educational activity must be made towards increasing the quality of the didactic materials, but also of the teaching form, for applicative courses and activities in the portfolio.

With regard to the course activity, I intend to improve existing didactic materials through thematic developments and approaches that are based on the detailing and updating of the reference biography for the Systems Engineering domain.

Beginning with the academic year 2014-2015, I proposed the introduction of two new disciplines in the curriculum: Discrete events systems – undergraduate cycle and Complex systems control strategies – master degree cycle. For this purpose, I intend to elaborate course/laboratory materials which, in correlation with the thematic content dedicated to these disciplines, contain results of my own research in the direction of DES modeling and simulation, as well as in the direction of control process.

Moreover, I believe that I will have to rethink the contents of the course materials, taking into

consideration the points of view expressed by the students in the appreciation charts for my didactic activity. For this purpose, I intend to enrich the course and laboratory materials, with practical examples that enhance the understanding capacity for certain theoretical notions.

I wish to continue the teaching activity in the form of interactive lectures, in which the teaching activity is interrupted by free conversations with the students, on the basis of the approached subjects. This represents a teaching method that may transform the knowledge transfer process into an attractive and participatory form of their assimilation. To that end, I wish that all teaching activities be supported by electronical presentation materials, so that they respect the thematic content of each lecture; however the general presentation has to be focused on the free, interactive and attractive transfer of knowledge.

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INDEX